SKI Report 96:70

Revised edition

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November 1996

ISSN 1104-1374
ISRN SKI-R--96/70--SE

SKI
STATENS KÄRNKRAFTINSPEKTION
Swedish Nuclear Power Inspectorate

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November 1996

SKI Project Number 95056

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November 24, 1996

RISKS FROM NUCLEAR WASTE

CONTENT

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SUMMARY

The first part of this review discusses the importance of *risk*. Man seems to have a longing for risks, like a part of the human nature. If risks are missing, they have to be invented, as needed parts in the emotional attraction of sports, amusement parks, traveling, etc.; this is the *emotional part of risk*. There is also a *rational part of risk*, in selecting such objects in ordinary life big industry, with a technology poorly understood by the general public, is a favored target. In that category no better choice can be made than the nuclear industry in general, and the nuclear waste in particular. To the public, through laymen like journalists and politicians, the risk from nuclear waste seems only to be treated emotionally, while to the scientists and technicians it is an object of exact calculation: probability of accident times consequence. If there is any relation between the emotional and the rational risk perceptions (for example, it is believed that increased knowledge will decrease emotions), it will be a desirable goal for society, and the nuclear industry in particular, to improve the understanding by the laymen of the rational risks from nuclear energy. This review surveys various paths to a more common comprehension -- perhaps a consensus -- of the nuclear waste risks.

The second part discusses *radioactivity* as a risk factor and concludes that it (becquerel) has no relation in itself to risk, but must be connected to exposure, either external or internal, leading to a *dose risk*, i.e, a health detriment, which is commonly expressed in terms of *cancer induction rate*. Dose-effect relations are discussed in light of recent scientific debate.

The third part of this report describes a number of *hazard indexes* for nuclear waste found in the literature and distinguishes between *absolute and relative risk scales*. The relative risk is obtained by dividing the risk value associated with the source (e.g. a waste repository) by the risk (derived according to the same principle) of some known risk source (e.g. a uranium ore deposit in nature). The absolute risks as well as the relative risks have changed over time due to changes in radiological and metabolical data and by changes in the mode of calculation. Some of the effects of such changes are summarized in two Tables and an Appendix, and in a number of diagrams showing different absolute and relative risks vary with radiation protection data, reference choice, waste source, and time.

To judge from the literature, the risk discussion is huge, even when it is limited to nuclear waste. It would be very difficult to make a comprehensive review (or, rather, brew) where all viewpoints are digested, and from that extract the essentials. Therefore, we have chosen to select some publications, out of the over 100 at the end of this report, which we summarize rather comprehensively; in some cases we also include our remarks.

SAMMANFATTNING

I rapportens första avsnitt diskuteras betydelsen av *risk*. Vilken betydelse man än vill lägga in i detta begrepp, så tycks det vara starkt kopplat till människans natur. Människan tycks ha en benägenhet att uppsöka risker, och saknas sådana så måste de skapas, t.ex. i sport, nöjesparker, resor, etc.; detta kan sägas utgöra riskbegreppets *emotionella del*. Det finns också en *rationell del*; härför väljes lämpliga riskobjekt, t.ex. tung industri med en teknologi som är dåligt förstådd av allmänheten; i denna kategori tycks kärnkraftindustrin vara ett favoritobjekt, i synnerhet dess avfallshantering. Allmänhetens uppfattning om det radioaktiva avfallet, vanligtvis förmedlad av lekmän t.ex. journalister och politiker, är genomgående emotionell, medan vetenskapsmäns och teknikers inställning präglas av rationella värderingar: sannolikheten för olycka multiplicerad med dess konsekvens. Om det finns ett samband mellan emotionell och rationell riskuppfattning (t.ex. anses ofta att ökad kunskap kan minska rädslan för en viss risk), då bör samhället, inklusive kärnkraftindustrin, verka för att allmänhetens kunskap om kärnavfallets risker höjes. Denna rapport analyserar olika sätt att nå en mera allmän förståelse -- kanske en enighet mellan alla grupper -- om kärnavfallets risker.

I det följande avsnittet diskuteras *radioaktivitet* som en riskfaktor; slutsatsen är att becquerel-tal i sig inte kan ge en riktig uppfattning om en risks storlek. Sådana tal måste kopplas till exponeringen för den radioaktiva strålningen, externt eller internt, ledande till en *dos-risk*, som vanligen uttryckes i form av en sannolikhet för *uppkomst av cancer*. Det nu använda dos-effekt-sambandet diskuteras i belysning av den vetenskapliga debatten härom.

Rapportens sista avsnitt beskriver de olika val av *risk-index* (hazard indexes) för kärnavfallet, som förekommer i den vetenskapliga litteraturen, där man skiljer mellan *absolut risk* och *relativ risk*. Den relativa risken erhålles genom att dividera riskvärden för källan (t.ex. ett avfallsförråd) med risken (beräknad enligt samma grunder) från en känd källa (t.ex. en uranmalm i naturen). De absoluta riskvärdena har i likhet med de relativa förändrats med tiden beroende på bl.a. ändrade radiologiska och metaboliska indata. Konsekvenserna härav sammanfattas i tabeller, appendix, och i ett antal diagram som visar hur sådana absoluta och relativa risker varierar med strålskyddsnormer, val av referenskälla, avfallets ursprung, och med tiden.

Risklitteraturen är mycket omfattande, även den som bara avser radioaktiva avfallslager. Det är närmast ogörligt att sammanfatta denna i sin helhet och att därur destillera fram allmängiltiga slutsatser. I denna rapport har därför valts ett annat sätt: ur de mer än 100 referenserna till denna rapport har ett antal utvalts, som refereras mera ingående, och där slutsatserna kommenteras.

1. INTRODUCTION

In man's pursuit of happiness, which is said to be the ultimate goal of living (85ADL), man looks with anxiety on all risks confronting him and takes all available measures to avoid them. In modern society social safety systems have to some extent relieved man of the paramount worries: to get food, clothing, housing, protection against harm, etc. However, to worry about the future is a natural instinct. Recently L. Sjöberg (96SJÖ) pointed out that risk aspects has a higher priority to most man than taking chances to improve living conditions. Therefore, man (i.e. mankind) looks for all kinds of disturbances on his pursuit of a good life. No easier target can be chosen than industrial technology, the opposite to the "good, old (and illusory 'safe') days". Some 60 million people, soldiers and civilians, were killed by the enormous amounts of weaponry produced in factories during the two world wars, climaxed by the atomic bomb. This creates a picture of industrial technology as something evil, and the main obstacle not only to man's goal of achieving happiness but also to the survival of mankind.

Still, from an evolutionary standpoint, succeeding or failing in the risk race has formed present man, the survival of the fittest (Charles Darwin 1859). Even though news media argue for zero risks, this is probably not of advantage to the society, at least not in the long perspective.

If industry is the main target of anxiety, which industry to designate as the foremost culprit? Some psychological facts can explain why the nuclear industry was chosen.

The industrial and post-industrial society has become too complex to understand for most people, based, as it is, on technical diagrams and economic tables, statistics, predictions, etc. Non-professional people can only digest simpler – or even only simplistic – pictures, as those commonly presented in the news media. Feelings will dominate over figures, something which is also scientifically proven. Adding the journalistic fact that "bad news sell better than good news" – possibly a consent to the human desire of anxiety – the public has been fed by a long list of "risks" from industry, and in particular from the nuclear industry. And partly correctly as the nuclear industry is *big industry*, and the threat is assumed to be larger the bigger the industry is.

Nuclear reactions and radioactivity are outside common knowledge – they are "inhuman", as some clergymen claim. Radiation risks are of concern also to the technicians, of course, but for a different and more professional reason; usually their large number of data and practical experience show that risks can be well controlled and that they are exaggerated in the public debate. However, the many figures and the extreme safety precautions adapted by the nuclear industry only heightens anxiety: "When they have to make such efforts to improve safety, then it must be terribly dangerous". One of the main problems in the relation between technicians/scientists and the public/journalists is *the lack of a comprehensible risk scale*, i.e. something which ordinary people can understand and compare with. This point is reiterated in numerous scientific publications, some reviewed in this report (e.g. 91SUZ). It may also be noted, that between the public and the technicians stand confused politicians, which are of little or no guidance to the layman (e.g. 89HAN).

It is important already in this introduction to realize that we deal with two risk aspects: 1) the public perception of the risks from the nuclear industry, and 2) the scientific/technical quantification of the risks. In this paper we mainly discuss the quantitative risks from the radioactive waste. We focus our interest on the *relative risk* rather than the absolute risk of the waste, i.e. what in society or nature to compare the risk of the nuclear waste with; this is actually a bridge to the public perception of the risk. A goal of these efforts is to find a useful and easily understandable risk comparison standard.

At the end of this report (§13) we review some literature on nuclear waste risks as presented by "nuclear people". In the main text we compare the risk concepts and comment upon difficulties, comprehensiveness, etc. Excellent reviews have recently been presented in this field, e.g. by 95KAN, of which we also include a review. In this context, it is unavoidable to discuss the application of the (radiological) no-threshold linear-dose-effect relationship, as it is at the root of the whole risk debate; we quote some critical publications in this field to get further perspective of the risk debate, particulary recent findings presented at the IRPA'9 congress (Vienna april 1996). Finally, we admit that we are no experts on risks; but only concerned nuclear chemists.[1,2]

2. WHAT IS A RISK? SOME GENERAL COMMENTS

The Webster Dictionary definition of *risk* is "the possibility of suffering harm (or loss)". Risk is more a concept than a simple word. In Roget's Thesaurus, synonyms of "risk" are danger, gamble, investment, probability, uncertainty (also indecent, risqueé, when using French spelling). We talk about political risks, economic risks (credit risk, etc), psychologic risks (risk of losing ones face), health risks, risk of failure (of some equipment), etc. A recent report (95ORN) on the risks of the nuclear fuel cycle includes *externalities*, i.e. health effects to the general population due to transportation accidents, impact on environmental quality, etc. "Risk" (especially, radiation risk) has become emotionally loaded, something bad that we should try to completely eliminate from our life. (So also with "waste", making nuclear waste a prime hate object.)

Risks can be divided into two main categories:

I. Risks which can be derived objectively and thus quantified (we call this the *quantitative risk*). This risk is a product of two properties:

$$Risk\ (R) = Probability\ of\ occurrence\ (P) \times Consequence\ (C) \qquad (1)$$

This is the common scientific definition of risk. For example, parachute jumping involves a very serious consequence although its probability of occurrence is small. On the other hand, the probability of getting a flue is usually high, but the consequence only moderately severe. Rasmussen (74WASH-1400), Hubert (94HUB), and others present risks in diagrams showing the probability of accident versus the severity (number of fatalities per accident).

It may be difficult to get reliable numbers of consequences when they can be described in several ways. Lindell and Sjöberg (89LIN) therefore consider expression (1) to be only "semi-scientific"[3]. However, a consequence can often be described with greater accuracy (a bang if something hits a drum), than its probability of occurrence (hitting the drum by throwing stones). Probabilities can only be based on a large volume of experience (experiments) and are described by statistics, which allows rare but large deviations, particulary when low numbers are involved (e.g. few experiments).

II. Risk as a (psychological, perceived) feeling, which cannot be objectively quantified (we call this *the qualitative risk*[4]). *Feeling of risk* can occur also to animals. The psychological

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[3] This is a somewhat surprising statement by the former head of the Swedish Radiation Protection Institute (SSI) as SSI has rigidly adhered to the radiological no-threshold linear dose-effect relationships to predict cancer deaths from radioactive releases (se also §4).

[4] If risk according to I is semi-scientific, then risk according to II may be classified as "un-scientific". However, we do not suggest such a simplification.

risk perception may therefore be considered as a *natural instinct*, closely related to (but not identical with) the survival instinct. Some risks may be perceived both by man and dog (e.g. to be run over by an approaching car), while others may be experienced only by man (to receive a parking ticket).

Extensive risk research is nowadays carried out by most serious organizations. While technical organizations like the Swedish Nuclear Power Inspectorate (SKI) does risk analysis according to aspect I, above, other serious organizations like The Swedish Risk Academy (SRA) and the Center for Risk Perception (CRP) are mainly concerned with aspect II. It may be illuminating
to list the SRA principal study subjects:

1. identification of a risk,
2. the size of the risk and its consequences (if it occurs),
3. is the risk acceptable,
4. how to inform of the risk,
5. what protective steps can be taken to avoid the risk,
6. how to control the risk, and
7. how is the risk perceived.

This list covers all aspects from vague human feelings to industrial hardware and may involve people of all groups of society. Maybe, this is what society is.

The CRP researchers at the Stockholm School of Economics point out that it is impossible to describe a risk of type II with a single numerical value, as too many non-quantifiable aspects (for example, ethical) turns up in the single concept "risk". The SRA sums up this situation by describing "risk" as a "multifactorial" concept.

In this report, we will only deal with quantitative risks (aspect I), though we readily admit that the psychological experience of risk is an important issue in presenting scientific risks to the public – perhaps the most essential one in case of risks from nuclear waste.

3. NUCLEAR RISKS

To-day most industrial countries require that risk analysis of nuclear power cover statistical, epidemiological, technological, environmental, psychological and economical aspects (91SESEE). After the IRPA'9 meeting one would like to add: biological and genetic aspects, too. However, risk in nuclear technology and science usually has a more limited scope and means either (i) possibility of some physical accident (reactor accident, accidental waste releases, etc), and/or ii) radiological accident (exposure to radiation). Normally the first risk is assumed to be followed by the second one.

Risks can be classified according to probability of occurrence. Thus SKI in Sweden uses the scale (i) high risk, if the probability of occurrence is >0.01, in which case the risk must be addressed, and (ii) normal risks with a probability of occurrence of <0.01. In the US (i) all kinds of risks from nuclear power must be $<0.1\%$ of all other accidental risks, while (ii) the radiologic risk to the population is prescribed to be $<0.01\%$ of all cancer risks (91HÖG).

In this report we will not discuss accident probabilities. Reactor accidents have been extensively analyzed in a large number of studies, the most prominent ones being the Rasmussen report (74WASH-1400) and studies of the Three Miles Island accident. The probability of a nuclear waste accident, although included in the 91SESEE study, has not been analyzed with equal rigor, although much effort is presently put into that subject by the national waste authorities.

Although severe reactor accidents have occurred, people (in 1995) seem to have been convinced that a "Chernobyl-type" accident is not likely to occur in modern LWR's (BWR or PWR). Polls indicate that the main worry of the public is the "risk of the radioactive waste", which "cannot be safely stored". Even if the "waste risk" only is a small leakage of radionuclides from a repository, it may still "poison the population" and "threaten future generations". Though this risk formally belongs to the small ones, perhaps the smallest nuclear accident[5], presently it causes the greatest public concern. In this report we only discuss this latter risk, though – with reference to eqn. (1) – only the "consequence (C)" term, sometimes referred to as the intrinsic (radiologic) risk of the nuclear waste.

4. THE SOURCE TERM, NUCLIDE DECAYS

The radioactive source may be a whole reactor, the spent fuel annually taken out, the radioactivity contained in a spent fuel storage basin or deposited in an underground repository at a given time. Because of decay, the source term always decreases by time. For the products in spent fuel elements, the source term is conveniently 1 kg or 1 ton of spent fuel (not counting grid, hulls, etc) from some type of reference reactor (usually a 1000 MWe reactor at 33% thermal efficiency, burning out the UO_2 fuel to 33 000 MWd/ton). The spent fuel elements are cooled (1-3 years) in the reactor storage pond, and then perhaps transported to a central storage facility (CLAB in Sweden) were they are further stored for up to 40 years under water. They should then be recanned and deposited in a final repository. Thus a number of "dates" can be given for the source term. For simplicity, *data in most reference sources begin at 1 or 10 years after discharge from the reactor.*

Historically, the first comprehensive information on formation of fission products and actinides in neutron irradiated uranium was obtained from declassified documents of the Manhattan Project (around 1947). A selection of such papers was edited and published in a series of volumes (National Nuclear Energy Series, McGraw Hill Book Co, New York) in the early 1950-ties. Detailed decay curves were presented by 58PRA (Fig. 1) before computer calculated data became available. More exact values on the amount of products in spent reactor fuel was later obtained by various computer codes, e.g. ORIGEN (73BEL), ORIGEN 2 (80CRO), OREST (88HES), BEGAFIP (72ELK), etc. Many more or less complete sets of data have been published for various reactors, modes of operation and fuel cycles. In general, minor deviations between these sets of data are observed, even for identical input data (see e.g. 80OLS/HÄG/SVE for a comparison of test results). These differences originate from (i) different ways of handling the effect of neutron energy spectra on cross sections, (ii) differences in the mathematical methods and approximations used, (iii) differences in the assumed time dependence of neutron energy spectra and fluxes, (iv) different self-shielding corrections, etc. However, these minor differences are insignificant for risk analysis, and the data are in all cases probably good enough for use in this context. As a comparison, ALI-values[6] are usually not given with more precision than 1 digit, i.e. ± 10 to $\pm 50\%$ precision (depending on the numerical value of the single digit).

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[5] If the collective dose commitment concept is combined with the no-threshold linear-dose-effect, however, the "poisoning" of the population by low radioactivity contaminations of drinking water can be shown to be the largest risk.

[6] Annual Limits of Intake (ALI), in Bq/year, for occupational exposure are calculated for radionuclides by the International Commission on Radiological Protection (ICRP). An intake of one ALI per year corresponds to a total committed dose equivalent of 50 mSv per year.

In the 1974 Rasmussen Report (74WASH-1400) the release of various radionuclides was calculated according to (estimates of) their high-temperature chemistry. This required, of course, reliable source terms (nuclide composition of the reactor core). The importance of having good source term values became evident at the Three Miles Accident 1979 and the Chernobyl accident 1986 (actually, no "true" source term is known). At the present, data for our "source term" (i.e. nuclide composition of the spent fuel) are for some major nuclides best obtained from pin-cell calculations using reactor physics codes. However, such codes only treat a limited number of fission products (and some reactor codes use hypothetical fission products as stand-in for the real ones in order to simplify the computations). To obtain more detailed information on all nuclides in the fuel one is normally forced to use special isotope generation codes and accept their relatively lower accuracy. However, lack of detailed data on reaction cross sections as function of neutron energy for many of the shorter lived fission products and some minor-actinide isotopes makes it at present futile to try to make more accurate calculations. Table 1 gives some typical data for the abundance of the most important (with regard to potential risks) nuclides in fuel from some different reactor types (data mainly from 74MCG, 75HAU, 80OLS/HÄG/SVE and 90LIL).

5. RADIOACTIVITY AS A RISK FACTOR

It is the radioactive source which is (considered to be) the origin of the risk to the environment. The simplest way to express the size of this risk is to give its radioactivity, i.e. the sum of the activity in becquerel (earlier, in curies, Ci) of all radionuclides ($A_0 = \sum A_i$ Bq). We shall call this the *radioactivity hazard*; in our waste toxicity list, Table 2, we number it A.

The radioactivity *per se* gives inadequate information and must be related to an amount or volume of matter[7] as listed in Table 2, yielding different kinds of *specific radioactivities*:

- B1 per gram or mole of the pure element;
- B2 per gram or ton of heavy elements (or, sometimes, oxides) e.g. in spent fuel; Fig 2 (77KJE);
- B3 per kWh electric energy produced (to compare with different energy producers);
- B4 per weight or volume of liquid (reprocessing waste concentrate) or solidified waste (e.g. glass); etc.

Numerous diagrams of specific activity versus time have been presented as parts of different waste management analyses. In the following, Q_0 will be considered to be specific activity (commonly per ton heavy element (U + Pu + Np + etc) charged to the reactor; if needed UO_2 is recalculated to pure U).

The specific activity, in whatever dimension given, is not an easily understandable risk criterion. For example, what information does 10^{12} Bq/ton spent fuel element (say, at time 100 y) provide? Therefore, the radioactivity of the waste must be compared with something in nature, and for this purpose uranium ore is commonly chosen; see Table 2, C1. This is done (i) e.g. in a Figure, either by giving reference lines for the activity from some chosen uranium ore, Q_{ref} (Fig. 3), or (ii) by dividing Q_0 by Q_{ref} which yields a dimensionless "risk" number. Q_0 / Q_{ref} may be given for radioactive waste glass, in which case Q_{ref} is the radioactivity of an

[7] Strangely enough, common people often seem to believe that "radioactivity" (or "radioactive radiation") can exist in some immaterial way and do not know that it is a property of matter. Here it is a need for public education!

equal volume of uranium ore. The reference may be 0.2% Uranium ore, but reference lines (in a Figure) are sometimes also given for higher or lower grade ores.

Still, this ratio (or comparison) is an insufficient criterium as regards human health risks. If the source is outside the organism, it is mainly the gamma-rays which produce the hazard (usually whole body irradiation). If the radionuclides are ingested into an organism, the radioelements accumulate in different organs, causing different damage to them. We therefore treat external and internal risks separately below:

(i) When the source is outside the body, as for most cases of natural background radiation and for exposure to radiation in handling nuclear waste, an appropriate hazard index would be to weight the activities (in Bq) by their gamma-energies (see e.g. 77COH). The exposure is given in units of gray (Gy) and can easily be measured by conventional instruments. Knowing source strength, composition, geometrical conditions, time of exposure, etc, it is straight forward to calculate an average expected whole body equivalent dose (in sieverts, Sv) to the exposed individual.

(ii) For (risk of) internal exposure one must take into account the transport of the radionuclide to man, way of ingestion/inhalation, the chemical properties of the radioelement/-compound, organ affinities, biological (as well as radiological) half-life, and the conversion factor to relate radioactivity (Bq) to dose rate (Sv/s). Several of these aspects are contained in the so-called *transfer coefficients* available for all radionuclides. Values of transfer coefficients are given by ICRP, UNSCEAR; etc.; see also 90BER.

For both, the risk analysis requires a third link, i.e. the relation between the human dose (Sv) and effect (cancer incidence or other harm). This final point is crucial for any risk conclusion, of course, because if there was not such a dose effect relation, there would be no risk. This last point needs some further comments.

6. DOSE BASED RADIOLOGICAL RISKS

The ultimate *radiological consequence* of radiation is death in cancer, except for very high doses ($\gg 10$ Sv). However, there are less severe consequences of radiation exposure: induction of curable cancer (as most thyroid cancers), genetic damage, observed cell damage (frequency of aberrant blood cells, chromosome abberations, etc.) without observable somatic or genetic effects, etc. These consequences are all collected under the name of *detriment*. We may then rewrite expression (1) as

$$\textit{Radiological risk} = \textit{Probability of occurrence } (P) \times \textit{Health detriment } (Det) \qquad (2)$$

90ICRP#60 calls this risk "the mathematical expectation of consequence". The detriment must always be specified, as different detriments (as for example bone sarcoma and leukemia) have different probabilities and causes, and are therefore not directly comparable (62UNSCEAR). If the detriment is not specified, the radiological risk usually refers to cancer death.

There is an essential difference between expression (1) and (2). For (1) it is more or less implicitly understood that it relates to a short time scale: "If I do this now, the consequence will follow very soon". For radiological risks, the health detriment of irradiation (brief or long) may lead to consequences 10 or 20 years later, as some cancers have very long induction time. A dose commitment concept has therefore been introduced: 90ICRP#60 states that "a radiation dose, when delivered, will involve a *risk commitment*, i.e. a commitment of increased cancer death probability rate in the future". It was originally introdused as a practical concept to estimate the risks of radioactive fall-out from nuclear weapons tests. The total dose delivered to the population now and in the future from a bomb test was called the dose commitment of

the population due to these explosions. The dose commitment is a useful regulatory concept for radionuclides taken up into the body (through inhalation, food, etc) if they are slowly excreted and have long half-lives (typical for ^{90}Sr), as they will deliver radiation doses for a long time. The dose commitment is rarely used for individuals but for large groups of people (the Marshal islanders, people exposed to Chernobyl fall-out, etc), then in the form of a collective dose: *the collective dose commitment* (D2 in Table 2). This is very useful concept for surveys of radiation risks over large areas, but is associated with some question marks, see §6.3.

In general, the dose risk from radionuclides may be expressed in the following ways:

- as dose risk (Sv),
- cancer induction risk (probability to contract cancer after a given dose),
- as a collective dose risk (man-rem, man-sievert),
- as number of "allowed doses"
- as number of cancer doses
- dose-based relative risks (dimensionless)

These risk concepts are directly related to the dose value and independent of the radionuclide pathway to man; we describe them separately in §§6.1-6.5. However, when the radionuclides appear in air, water or food it is more convenient to make the risk analyses via their relative concentrations (Bq per m^3 or kg) in the matrix material; we describe that in §8.

6.1 Risk expressed as dose value

For a known pathway of a radionuclide to man, one can calculate the external exposure and the uptake into the body of the radionuclide, and the dose received by the exposed man in a given time period. This method has been extensively used in the Swedish Nuclear Safety (SKB/KBS) project, where the dose rate (in Sv/y) to man exposed to radioactive groundwater leaking from a waste repository was calculated. (Note, that doses from individual nuclides always must be summed into a *total dose*.) A common criticism is the extension of the calculations to millions of years (maybe cancer is curable within 50 years, will geology and ground water conditions remain unchanged, what life style will men have, will he even exist, etc ?). There are some advantages by the use of a *dose value* as a measure of risk in that it may be compared with natural doses, which – to some extent – avoids the question of the effect of the dose. The drawback, of course, is that the dose value *per se* is incomprehensible to the common man; he will have no way to interpret the "KBS-curves".

6.2 Relative dose risk

In 62UNSCEAR it is stated that *only relative risks of irradiation can be given*. In 1962, sufficient reliable information was only available for leukemia and bone cancers. The effects of natural radiation was then taken as standard, to which effects man-made doses were compared: the radiological risk was expressed as the ratio between the dose from the man-made sources and the natural radiation dose. Thus a dose 200 times the natural background dose was assumed to carry a 200 times larger risk for contracting leukemia than the natural frequency (which is 4.5 cases per 100 000 people per year in the Nordic countries). We may call this the *dose-based relative risk* (Table 2, D3). Thus, in expression (2), P and Det are not separately evaluated. It may be of interest to note that in 62UNSCEAR no absolute cancer death figures were given. Mathematically, the dose based relative risk (*DBRR*) can be stated as

$$DBRR(\text{dimensionless}) = D_{E,t}\ (\text{Sv}) \,/\, D_{\text{ref},t}\ (\text{Sv}) \qquad (3)$$

where $D_{E,t}$ is the exposure of an individual compared to some reference value, which is $D_{ref,t}$ (Sv), as for example the natural background radiation ($D_{nat,t}$ Sv); t indicates that the doses should be delivered during equal times.

The dose based relative risk has not been directly used, except in principle in 31WIN and UNSCEAR. It could without great complication be introduced e.g. in the SKB analyses. Instead of this approach, relative hazard indices have been developed, §9.

The application of expression (3) may lead to a confusing consequence as regards the "normal background radiation": for the same exposure, living in a higher background radiation area would constitute a lower risk! This may be a controversial conclusion, if it is not assumed that people become more radiation tolerant in higher background areas. About this, we presently know nothing!

6.3 Committed and collective dose risks

Fall-out, accidental reactor releases, releases from the waste handling, etc, involve small radiation doses to a large population. If the individual doses are summed one arrives at a total dose in *man-sievert*. This dose is referred to as the *collective* dose. According to the *dose-effect relation* (§§6.4 and 7) the effect of a collective dose of 100 man-Sv will be the same either 10 persons receive 10 Sv each, or 1000 persons receive 0.1 Sv each. It is common to express and compare the radiological risk simply in man-Sv. This is used by the United Nations in their UNSCEAR surveys of Sources and Effects of Ionizing Radiation, which is the most extensive and up-to-date publication on radiation doses from man-made and natural sources; see Table 2, D2. The man-Sv concept is probably more difficult to comprehend by the layman than the Sv.

In order to relate the emissions of radioactivity from nuclear power installations, or the accumulation of radioactivity in the body from fall-out, to resulting life doses, the ICRP has introduced the *committed dose* concept, which is the total dose contribution to a person or the population over all future years of a specific release or exposure; for practical reasons, the time is commonly limited to 70 years for a person, and 500 years for a release. The unit is either a life-time dose (Sv) to a person, or the infinite (500 y) time integral of the man-Sv/y dose rate to a population (man-Sv). Radiological health protection organizations often require the nuclear power producers to provide committed dose calculations; even though they seem not yet to have been used in waste management, it is likely that they will be applied in the future to compare different fuel cycles and waste management schemes.

6.4 Cancer induction risk

If cancer death is used as the consequence of receiving a certain radiation dose, it is necessary to have some probability factor relating the dose received with the cancer death frequency. Presently, ICRP and UNSCEAR set the cancer induction risk at 5% per sievert received for low-levels of low-LET radiation. Thus we can write

$$\textit{Cancer induction rate } (LD_c) = 0.05\ H \quad (\textit{cancer fatalities per Sv}) \tag{4}$$

where H is the dose received in sievert. Formally, a dose of 20 Sv received by one individual carries a 100% probability for that person to die in cancer some time in the future, perhaps a long time after the end of the exposure, neglecting dose rate effects. As a whole body dose of 20 Sv given in a short time is lethal ($=LD_{50/30}$, i.e. lethal dose in 50% of cases within 30 days), expression (4) is only applicable to low dose rates. It was originally derived as a guideline for safety arrangements, not to predict cancer fatalities. Nevertheless, as the cancer induction risk increases with dose, it may be appropriate to use the dose as a cancer risk index. This is e.g. done by Cohen (77COH, 78COH) who calculates the dose received by the body and multiplies it by expression (4) to yield the risk in *number of cancer doses* (or *cancer*

deaths), D4 in Table 2. Because expression (4) is fundamental to the risk analysis, we will discuss it further below (§7).

6.5 Number of allowed doses, recommended dose limits, lethal doses, etc.

In 1953 the US National Committee on Radiation Protection (53NCRP), and in 1955 ICRP (55ICRP), set out rules for *maximum allowable radiation exposure*, limiting it to 5 rem/y for individuals of age > 18 y. This value has been revised, and in 90ICRP#60 the *recommended dose limit* is 1 mSv/y for the public ($D_{0.001}$) and 20 mSv/y ($D_{0.02}$) for occupational workers. By dividing the actual dose received by these (or alternative) dose limits, one obtains a figure indicating the *number of allowed doses* or *dose limits* (dimensionless), which indicate how hazardous or relatively safe the work is. E.g. if $D/D_{0.001} > 1$, the work exceeds recommended dose limits and is considered unsafe, and action should be taken to reduce the radiation exposure. Alternatively, if one nuclear fuel management concept leads to a $D/D_{0.001}$ ratio of 10 000 (e.g. for the U/Pu reprocessing cycle)), and another to a ratio 5 000 (e.g. for the once through cycle), these ratios can obviously be used for risk analyses of the different concepts.

A more complicated comparative risk index is the *loss of man days* in the nuclear industry as compared to in some other method of producing electric energy, as used by 79INH and others. This concept requires evaluation of disabilities other than deaths; e.g. for coal as an energy source it covers all steps beginning at the coal mine (accidents, air and water pollution, coal dust lung illnesses, etc) to the kWh fed into the electric grid. Such risk analyses, and comparisons, may include numerous societal choices, as described e.g. in 75OTW or 91SESEE.

It is obvious that the principle of using dose ratios can be applied to any kind of radiation dose ("allowable", "recommended dose limit", "cancer dose", etc) as long as we define the bases for calculating the dose ratio. 77COH compares the number of cancer doses, calculated as above, with number of *lethal doses of toxic substances* produced by the chemical industry; e.g. if the lethal dose of chlorine is 3 mg/m^3 and the annual production is 10 million tons (the Common Market in 1986), obviously $10^{13}/3 = 3 \times 10^{12}$ lethal m^3 of the gas is annually produced; this can, for example, be compared to the number of committed cancer doses produced annually by the nuclear industry to provide a relative risk scale. In contrast to radiation, toxic chemicals have threshold values, below which they are regarded as non-lethal or harmless. Risk from ingestion of toxic substances is usually given in grams per kg body weight.

7. DOSE-EFFECT RELATIONS

Risks from radiation have been discussed since the discovery of radiation damage from X-rays and from radioactive substances in the beginning of this century. For example, the paper 31WIN of 1931 contains almost all aspects which has been discussed in subsequent years: dose-effect relations, threshold value, repair mechanisms, harmless dose, etc. As these issues have been covered in numerous publications, the comments below are intended only as a brief sum up of various aspects, including present uncertainties of importance for the judgement of risks from nuclear waste.

The dose-risk relationship is a line in a graph showing the number of expected cancer fatalities versus radiation dose (in Sv). The "standard line" is given by eqn. (4), i.e. a straight line of slope 0.05 (fatalities/Sv). The line goes from origo, i.e. any dose, however small, increases the cancer risk; thus there is no threshold dose, below which the risk is zero. The main foundation for the assumption of a linear no-threshold relation is the radiation effects observed for the Japanese atomic bomb victims (doses in the range 0.2 to > 10Sv). All efforts

to find a convincing linear relation from 200 mSv down to zero has failed; the figure 200 mSv shall be compared with a common natural radiation background value of 2-6 mSv. "Expected" should of course be understood so that the cancer frequency is expected, provided nature can be described by this linear expression. In recent years it has become accepted that the slope decreases by a factor 2-3 (but not to zero!) at the lowest dose values (the "linear-quadratic relation").

62UNSCEAR (its Appendix H), discusses doses and estimates of risk. The deficiencies in the knowledge on the real dose-effect relationships is emphasized. Nevertheless it is assumed that the effects are proportional to the dose (as "observed for genetic effects of high doses on insects"), as "there is no other alternative". After many reservations, the report states that any other dose-effect relationship than the linear one would be too complicated to use. *62UNSCEAR clearly says that the linear no-threshold rule shall be used only for computational purpose (i.e. in making protective regulations), and that it is not a scientific (biological) truth.*

Already in 62UNSCEAR it is stated that carcinogenity at high levels of radiation is much too complex to allow the use of a linear dose-effect relationship. Nor can such generalization be made for late somatic effects. The relationship was questioned already at its introduction (58BRU). Many biochemists (e.g. 85YAL, 95SON), radiologists (73FRI), toxicologists (e.g. 91MOL), oncologists (e.g. 95WAL), epidemiologists (e.g. 80COH) etc. state that the rule lacks biological credibility: such a complicated process as induction of cancer requires many factors working together, some still unknown. If also the biological repair mechanisms is taken into account, the no-threshold straight line becomes highly unlikely (58BRU, 82LUC, 91CRU). For example, 82 LUC presents over 200 references in support of a beneficial effect of low-dose radiation. The complexity of cancer induction is illustrated in a simple experiment in which Walinder showed how it was possible to cause irradiated mice to develop cancer only by changing their diet (73WAL).

Doubts on the linear relation have recently been expressed by The Health Physics Society in the USA, by the French radiation protection organization (IPSN) and were most recently emphasized at the IRPA'9 (International Congress on Radiation Protection, Vienna, April 1996). At IRPA'9 it was described that (i) cancer induction beginning by a DNA-damage requires 3-4 additional biochemical disturbances before cancer growths occur, (ii) only some genes are pro-cancerogenic to radiation; the frequency of these genes are not statistically distributed, (iii) single-strand breaks repair to >99% in 2 hours, thus for natural radiation background, which allow months of repair time, probably all damage will be repaired. These results obtained from X-ray studies show that the no-threshold linear ("stochastic", see below) relation is contradictory to biological findings. In this connection serious doubts were also expressed about the collective dose concept.

Arguments for the no-threshold linear-line are to be found in most ICRP and UNSCEAR publications, but also some doubts, particulary in UNSCEAR. Modifying views are expressed e.g. by 77ERL, 80CRA, 94GON, 95MUC and many others. At IRPA'9 it was suggested that a meeting soon is arranged between the proponents and critics of the linear dose effect relation to sort out the discrepancies. The conclusions from such a meeting, endorsed by IRPA, ICRP, UNSCEAR, IAEA, etc. could have an important effect on the risk evaluation of nuclear waste repositories.

Unfortunately, the situation is a little bit more complicated for the nuclear waste, as it exhibits "two radiation risks", mainly from external (low LET) radiation from the gamma-emitting fission products and from internal radiation from inhaled or ingested (high-LET) alpha-emitting actinides. The debate about the linear relationship, above, concerns mainly gamma (and X-) radiation. Most researchers still accept the linear slope of 0.05 for high-LET radiation (at least at high doses). Is there a threshold for alpha radiation? This is related to the concept of deterministic and stochastic processes: it is a priori assumed that a

stochastic process (as the random contraction of cancer) cannot have a threshold, while a deterministic process, as the use of radiation for therapeutic purpose, has a threshold. Walinder and others question this philosophy. The biochemical and genetic studies presented at IRPA'9 show that radiation cancerogenesis is not a stochastic process, but so far only for X-rays. It may also be debated if the slow release of radionuclides from a waste repository to a well used by a family in itself is a stochastic or deterministic process?

In summing up, the basis for the risk analysis – that radiation at the low dose rates (and low total doses) expected from a nuclear waste repository is harmful – is in doubt. The outcome of this controversy will be important for the risk analysis and for the nuclear industry as a whole. The salient point now is that in expressing the risk of radiation in number of cancer fatalities, an additional term of uncertainty is introduced. It may not be a good choice to use a "cancer frequency" or "cancer risk" to describe the hazards of the radioactive waste, but presenting the risk in sieverts, without applying a dose-effect relationship, would be uncontroversial, though probably not very informative to the public.

In the rest of this paper we shall only present risk values in non-biological terms and make risk comparisons by natural comparisons (Table 2).

8. RADIONUCLIDES IN WATER AND FOOD

The risk expression in §6 is convenient for external X- or γ-radiation, which can be simply measured or calculated for whole-body doses. However, the main risk from nuclear waste comes from radioactive nuclides released into groundwater and transferred to potable water sources, or end up in food. The radionuclides ingested move to specific organs in the body where they deliver their dose for a time depending on biological and radioactive half-lives. To estimate the dose from this internal radiation, one must know (a) the concentration of radionuclides in food and potable water (and, eventually, in air in case of gases or aerosols), (b) consumption pattern, (c) relative uptake into body organs, which depend on the chemistry, and (d) biological half-life, which in turn depends on metabolism and decay properties of the radionuclides, (e) the conversion factor from radioactivity (Bq) to dose rate (Sv/s), etc. Dose conversion factors are available in many ICRP and UNSCEAR publications; se also 90BER. The exact calculation of doses is an extensive compartmental summation over time.

The calculation of the dose from radionuclides deposited in the body is quite complicated (59ICRP#2, 90ICRP#61). In 1953 the US National committee on Radiation Protection (53NCRP), and in 1955 ICRP (55ICRP) therefore introduced a new concept, the *maximum permissible concentration* (MPC) of a nuclide in edible/potable or breathable food/water or air, and the *maximum permissible body burden* (MPBB) of that nuclide (in the US this was referred to as the Radiation Concentration Guide, or RCG); the MPC_w-values refer to oral intake by food and water, while the MPC_a-values refer to inhalation by air. A daily consumption of food/water for 50 years would lead to the MPBB value. The MPC and MPBB values were set so that the weekly doses would not exceed 0.1 rem/week (or 5 rem/year) either for a 40 hr week (exposure only at work) or for a 168 hr week (continuous exposure). ICRP published an extensive report on MPC and MPBB values in 1959 (59ICRP), with details on daily ingestion values, critical organs, fraction taken up and reaching specific organs.

More recently, limits for the annual intake, ALI-values, have replaced MPC. The ALI-values are calculated using metabolical and organ weight data as given in "Reference Man" (ICRP#20) with the restraint that a continuous yearly intake of one ALI of a specific radionuclide should not give a larger dose equivalent than a chosen limit; at present 0.05 Sv/year. Appendix I lists MPC_w, present ALI-values and DWC. The ALI-values were mostly taken from the list in 90ICRP#61. To simplify the comparison with earlier publications, we will

use the abbreviations MPC and MPBB in the next paragraphs both for the older data from ICRP and for DAC-values etc. calculated from ALI-values and yearly intake of food, water, etc. The most recent ALI-values will be used in our calculations later in this report.

It is pointed out in e.g. 78ADA that i) the ALI value presumes that only the specified nuclide is responsible for the radiation dose, ii) that the data in "Reference Man" are mainly relevant for adult white males; eventual deviations caused by differences between sexes and differences between human races are not well known.

From the ALI-values recommended by ICRP in 90ICRP#61 it is possible to calculate the water and air concentrations that would give rise to one ALI during a one year continuous exposure. These concentrations are called derived air concentrations, DAC, or derived water concentrations, DWC. In principle DAC- and DWC-values can be used in place of the old MPC_a- and MPC_w-values. However, the ALI-value is more general and also useful in cases of short exposures, for setting limits on the amount of active material handled with certain precautions, etc.

9. WASTE TOXICITY AND HAZARD Indices

The MPBB and MPC values allow the introduction of new risk concepts for sources of radioactive nuclides which may enter into the human body. As we relate the risk to a condition of the source, the term *hazard* will be more appropriate than "risk". We will use the term *hazard index*, which was introduced in the early 1970-ties to describe the risks from nuclear waste (71BEL, 71GER, 72CLA). In Table 2, items E, we have summarized the hazard indices based on MPC and ALI, and which are commonly used in radionuclide waste risk analyses. An important observation is that the hazard index calculation in the ORIGEN code is based on MPC_w-data from 10CFR20B and not on MPC_w from ICRP. In general this leads to a factor of 10 higher hazard index values in ORIGEN output as compared to calculations based on ICRP MPC data, but several exceptions exist; see Table 4 and appendix A.

9.1 Radionuclide concentration based hazard indices

McGrath (74MCG) discusses risks associated with the radioactive wastes from different nuclear fuel cycles and different deposition concepts, covering risk aspects of the various steps of the cycle until the radionuclides reach the nutrition cycle. In comparable parts, this study is less comprehensive then those by the Swedish Nuclear Fuel Safety Management (SKB) which, however, only analyze specific waste management concepts. McGrath points out that the different chemical and nuclear properties of the radionuclides makes it necessary to treat each nuclide independently. An index containing all properties of an isotope is not realistic today; he suggests, because of lack of sufficient data and as a first approximation, the use of a *hazard index* (HI_i) defined by the relation (Table 2, E2)

$$HI_i\ (\mathrm{MPC_w}) = Q_i \,/\, MPC_{w,i} \quad (\mathrm{m^3\ water}) \tag{5a}$$

$$HI_{\mathrm{tot}}\ (\mathrm{MPC_w}) = \Sigma\,(Q_i \,/\, MPC_{w,i})\ (\mathrm{m^3\ water}) \tag{5b}$$

where Q_i is (the source term of) the radioactivity of isotope i in the waste mixture (Ci or Bq), and $MPC_{w,i}$ is its corresponding MPC_w (Ci/m^3 water or Bq/m^3 water) value (McGrath uses hazard index values from ORIGEN output, c.f. Table 4). For more than one radioisotope the ratio has to be summed over all i isotopes (5b). The index HI_i gives the amount of water needed to dilute the isotope to its MPC_w value. For the gaseous fission products McGrath recommends the use of MPC_a (Ci/m^3 air or Bq/m^3 air) values.

Noting that volumes of water and of air cannot meaningfully be added together, he suggests a *maximum permissible intake* index, *MPI*, which is obtained by multiplying the MPC-values by the annual intake volumes (0.8 m^3 water/y, and 7300 m^3 air/y), thus

$$MPI_{w,i} = 0.8\ MPC_{w,i} \quad (6a)$$
$$MPI_{a,i} = 7300\ MPC_{a,i} \quad (6b)$$

The MPI for any single nuclide is in principle the same as its ALI value, although it is calculated "the other way around".

Gera and Jacobs (71GER) suggest an alternative *potential hazard index*, *PHI*, which is defined as

$$PHI_i = P_i\ (Q_i / MPI_i)\ (T_i / 0.693) \quad (7)$$

where P_i is a factor "depending on the biological availability" and T_i is the half-life of the radionuclide. $0.693/T_i$ equals the decay constant λ_i. Thus eqn. (7) can be written as follows

$$PHI_i(t) = P_i\ (Q_{i0} / MPI_i)\ (T_i / 0.693)\ (1/2)^{t/T_i}$$

where t is time ($t = 0$ at $Q_i = Q_{i0}$). This eqn. can be used to evaluate the potential hazard index at any time. The usefulness of P_i is dubious as a number of factors enter in the "the biological availability". McGrath calculates PHI_i values for a number of fission products and actinides in 1 metric ton of fuel for times from 1 to 1 million years, and compares the results for different fuel cycles (see §10). It is interesting to note that eqn. (7) yields an infinite potential hazard index for all stable elements that has poisonous effects at any concentration.

9.2 Radionuclide body burden based hazard indices

Liljenzin, Rydberg and Svantesson in a series of papers (75SVA/LIL/RYD, 75RYD/LIL, 75RYD) find that the hazard index described by eqn. (5) is useful but may not be understood by laymen (What message will 10^{11} m^3 water give?). They therefore introduce the concepts of *MPBB hazard index* and *relative hazard index*. The MPBB hazard index, HI_{tot}(MPBB), is defined by (Table 2, E1)

$$HI_{tot}(\text{MPBB}) = \sum (Q_i / MPBB_i) \quad (8)$$

analogous to the MPC hazard indices (eqn. 5).

9.3 Relative hazard indices

The *relative hazard indices*, *RHI*, either based on MPC or MPBB values, are obtained by dividing the hazard index of the waste nuclides with a suitable reference value (Table 2, E1, E3), HI_{ref} for example the hazard index of uranium. Thus

$$RHI_{tot}(\text{MPC}) = \sum HI_i(\text{MPC}) / \sum HI_{ref}(\text{MPC}) \quad (9a)$$

The value of HI_{ref} can e.g. be calculated for several possibilities, e.g. (1) 6.1 ton natural uranium (this is the amount needed to produce 1 ton of 3.3% enriched uranium fuel at an

assumed concentration of 0.2% ^{235}U in the tails fraction)[8], (2) 1 ton of natural uranium, (3) 0.032 ton U (this is the amount of uranium consumed in the reactor at a burnup of about 30 MWd/kg). In this case it is necessary to sum over all nuclides, including all uranium daughters, both for the nuclear fuel and for the natural uranium). In next paragraph we will discuss the choice of various reference values.

The relative hazard index based on body-burden (*relative body-burden risk*, RBBR) of the waste nuclides may then be

$$RHI_{tot}(\text{MPBB}) = \sum MPBB_i \,/\, \sum MPBB_{ref} \qquad (9b)$$

Hamstra (75HAM) also uses the MPC-values to derive a *radiotoxic hazard measure* (RHM) index, which is the same as those defined by eqn. (5); he compares these values with those for 3530 tons of ore plus mill tailings, as this is the material assumed to be required to produce 1 ton of the uranium fuel. He also compares the RHM values for various fuel cycles, including the breeder cycle.

In a survey on the problems of nuclear waste in France, Guillaume (76GUI) introduces a waste hazard index "l'indice de risque radiotoxique" on the basis of MPC values (CMAP, for Concentration Maximale Admissible dans l'air ou l'eau de boisson pour le Public). Radiotoxicity indices are given for various reprocessing schemes (using different extractants) of spent light-water and fast reactor fuels with and without recycling the plutonium. As all waste is planned to be vitrified, the vitrified waste is used as reference. 89SRI also uses the m^3 water hazard index in discussing different types of fuel cycles where some of the waste nuclides are returned for further use in the reactor.

From around 1985 most publications on nuclear waste, including text books (e.g. 77EHR, 80CHO, 95CHO) seem to use some hazard indices similar to the above to make understandable comparisons. The first publication to put the hazard index of uranium ore to 1 seems to be 78KBS, which shows that at times $10^4 - 10^5$ years the waste products become less hazardous than the uranium ore from which they were produced.

In connection with the introduction of the ALARA principle (As Low [doses] As Reasonably Achievable) in 1991 the MPC-values were replaced by *ALI-values (Annual Limits of Intake)* (90ICRP#46). Thus, in calculations the MPC-values referred to above are replaced by ALI-values (or perhaps by the ALI-value divided by the yearly consumption of water or air). This will give hazard indices based on equations 5a and b with the dimension of "number of humans × time" or man-years instead of water volume; alternatively one may use "number of ALIs" (Table 2, E4). The switch to the ALI system, which is based on more modern biological and physical data than the old MPC/MPBB system, leads to remarkable changes between the hazard indices for several important radionuclides. As an example the potential hazard index of ^{90}Sr is 2.7×10^{-5} m^3 of water per Bq when using MPC$_w$ for a 168 hr week and 1.3×10^{-6} m^3 of water per Bq when using the corresponding ALI-based derived water concentration, DWC. The potential hazard index of ^{90}Sr has decreased by a factor of 20 when going from MPC$_w$ to DWC. The change span no less than four orders of magnitude from ^{237}Np (increase ca. 300×) to ^{71}Ge (decrease ca 0.03×). The most extreme changes are collected in Table 3. In Appendix A we give a complete list for a full comparison between MPBB, MPC, ALI and derived values.

[8] Due to variations in the operational cost, tailings from enrichment plants will contain from ~0.2% to ~0.3%^{235}U. Hence 6.1 – 7.3 tons of natural uranium is needed to produce 1 ton of 3.3% enriched uranium.

9.4 Other hazard indices

We shall only mention one more paper which discusses the use of either a waste *toxicity index* ("TI") or a *repository performance assessment value* ("PA"-value) to evaluate the long-term disposal risks; see 95KAN/HIL.

10. CHOICES OF HAZARD INDEX REFERENCE SYSTEMS

As mentioned above it is necessary to define a *reference hazard* in order to calculate relative hazard indices according to equation 9a (or 9b)[9]. It is also desirable that the reference system is quantitatively linked to the nuclear fuel cycle. Otherwise one would have to introduce some kind of normalizing function, e.g. if the potential hazard index of coal ash was our reference we could use the heat (or electricity) produced from a given weight of coal and from a given mass of nuclear fuel to normalize the two potential hazard indices before use in equation 9a; cf. 79INH. Some of the possible reference systems have been mentioned briefly, but here we will try to develop a reference system, the components of which can be added together, if desired, to generate a more complex reference system. In order to be general, we will normally refer to *heavy metal* (HM) as a common name for the two elements found in nature, thorium and uranium, and for other actinides that can be used to fuel nuclear reactors; in all cases we also refer to 1 ton (elementary) heavy metal as fresh nuclear fuel, *initial heavy metal* (IHM).

10.1 The ore hazard index, NOreHirs

The most common reference system used was the potential hazard of the amount of unbroken (i.e. native) ore which contains the same amount of heavy metal as a unit mass of unused nuclear fuel. We will call this *the native ore hazard index reference system* or NOreHirs in this report. NOreHirs is practically constant in time for millions of years to come. The basic value should then be 6.1 tons of U in ore (rather than 1 ton), as this amount is needed to produce 1 ton of 3.3% enriched (elemental) U in the fuel ("standard fuel") at a tailings content of 0.2% ^{235}U. Fig. 4 shows the relation between the mass of natural uranium needed to make one unit mass of enriched uranium as function of enrichment and the concentration in tails.

Only when the waste is solidly deposited in rock, may it be compared with the risk from an unbroken uranium ore. Therefore, the hazard from a waste deposit has been compared with the hazard of a uranium ore of same volume (or mass) (75HAU, 77COH). The comparison should therefore be made with a volume equal to that of the repository, including the rock inside the repository boundary. In order to bring this in line with the requirement of preceding section, the grade of the uranium ore to compare with must be properly chosen. Usually most studies compare with an 0.2% U ore. Other choices have been the natural average concentration of U in the ground (about 4 ppm) up to ores around 1% U and to pitchblende (60-70% U); cf. Fig. 10. Figure 13 shows how this index depends on time and data.

OreHirs cannot be used in a straight forward manner when spent fuel is reprocessed and the recovered material reused as fuel.

10.2 Total heavy metal hazard, THMHirs

A second alternative is to base the relative potential hazard on the heavy metal actually used to produce fresh fuel. We will call this *the total heavy metal hazard index reference system* or THMHirs. In case of uranium fuels, it is the potential hazard index of the mass of natural uranium used to produce the fuel. For a reactor operated on natural uranium this system is not

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[9] These hazards are, of course, only *potential*; for simplicity we do not repeat this all through the text.

much disputed. The same holds for reactors operated on the Th/U fuel cycle. However, for enriched uranium fuel this reference system can be criticized because the potential hazard of the depleted uranium (which remains somewhere) is included in the reference system but does not contribute to the potential hazard of the waste until after very long times (>100 000 y). THMHirs increases slowly with time as radioactive daughters grow in, see Figure 13.

10.3 Unused fuel hazard, UFHirs

A third choice is the potential hazard index of the amount of heavy metal in unused nuclear fuel. We call this *the unused fuel hazard index reference system* or UFHirs. The reasoning behind this reference system is that the heavy metal has already been produced for some reason, but we have a choice either to use it in some non-nuclear way or to use it as fuel for a nuclear reactor. The ratio between the potential hazard index of the spent fuel and that of a corresponding amount of heavy metal indicates the increased or decreased potential risk caused by our choice. UFHirs increases slowly with time until radioactive equilibrium is reached in the decay series, see Figure 13.

10.4 Mine refuse hazard, MRHirs

A fourth reference system is the potential hazard index of the mine refuse remaining from extraction of the heavy metal needed to make a unit mass of nuclear fuel. We might call this *the mine refuse hazard index reference system* or MRHirs. This value depends on the mining technology: surface mining means removal of lower grade rocks, in situ leaching leaves some 20% U in the ore body, etc., efficiency in recovering the uranium from the ore (usually 95-99%), and losses in the manufacturing steps (1-2%) to produce the pure UO_2. Therefore, in practice, to make 1 ton U-fuel a somewhat larger ore body has to be mined than "formally" needed from the average grade value. The leakage of U, Ra, etc. from this mine and manufacturing refuse constitutes a hazard, which cannot be neglected. Thus, MRHirs cannot be assigned a unique value as the radioactivity decreases continually with time, see Figures 5 and 13.

10.5 The consumed fuel hazard, CFHirs

A fifth system is the potential hazard index of the amount of initial heavy metal in the fuel, normally uranium, which has been consumed during reactor operation, either by fission or by conversion to other actinides. We might call this *the consumed fuel hazard index reference system* or CFHirs. CFHirs corresponds to a potential hazard that has really disappeared and been replaced by the potential hazard of the spent fuel or high level radioactive waste. CFHirs is constant in time, c.f. Fig. 13.

10.6 Others

Many authors have suggested other reference systems, in principle based on reasonable combinations of the five basic hazard index reference systems defined above. As an example, THMHirs plus the corresponding MRHirs has been used by Phlippen (see 96IAEA).

Figure 13 illustrates the value of the five basic hazard index reference systems (normalized to 1 ton, 3.1% enriched PWR fuel) as function of time. It is obvious from this Figure that the time variation and magnitude of any relative potential hazard index depends on the reference system used. We have tried to illustrate this in Figures 14, 15, 16, 17 and 18. These Figures show the total ALI-based relative potential hazard of 1 ton of spent PWR fuel (3.1%, 0.2% in tails) using five basic relative hazard indices.

11. HAZARD INDICES OF VARIOUS FUEL CYCLES

Although there are quite a number of choices in the risk analyses of the waste from the once through fuel cycle, it is still a rather straight matter. This is not so for alternative fuel cycles, when waste not has a single origin. However, it is important for comparison of the risk from different fuel cycles, for example with and without exhaustive reprocessing or partitioning with special actinide burners (cf. 76HAU, 78COH).

In order to simplify the case we will only treat a few typical fuel cycles. For thorium based fuels we will assume a thermal Th/U breeder of conventional design. For uranium based fuels we will only treat LWR:s operating on enriched fuel, a fast breeder using the U/Pu cycle and an accelerator driven fast Th/U breeder similar to the Energy Amplifier proposed by Rubbia. In the thermal and fast breeder cases reprocessing is used to recover uranium and plutonium. Sometimes the relative hazard from a single element, e.g. plutonium, is considered to be the sum of the relative hazard of all its isotopes and their progeny (96IAEA). This approach helps to identify the effect of chemical separations on the relative hazard of radioactive waste, but can also be criticized because it obscures the meaning of the relative hazard somewhat because some of the daughter elements may behave differently from their parent element in a repository environment and in nature in general. In our discussion of the relative hazard of the products from various fuel cycles we will instead aggregate the relative hazard for spent fuel and for high level waste.

11.1 The thermal Th/U breeder cycle

The Th/U fuel cycle has recently attracted new interest as a means to reduce production of plutonium by nuclear reactors and to increase nuclear fuel resources (see e.g. 96IAEA). However, most of the work on this fuel cycle was done many years ago. Calculated data on the composition of spent fuel, reprocessing wastes and hazard indices from a thermal high temperature thorium breeder have e.g. been published by McGrath (74MCG) and by Haug (75HAU). Figure 19 shows hazard indices for unprocessed fuel and high level waste for a thorium fuelled reactor operating on the equilibrium cycle (^{233}U recycling). The Figure includes the original curves by McGrath (74MCG), which were taken from ORIGEN output and based on MPC from 10CFR20B, and fuel hazard indices based also on MPC_w and ALI from ICRP. As hazard index reference one might use uranium ore or thorium ore data.

11.2 The thermal U/Pu fuel cycle

Figure 20 shows hazard indici for spent PWR fuel (33 MWd/kg, 3.1% initial enrichment at 0.2% tails) and high level reprocessing waste. Again, the effect of the different data sets (10CFR20B, MPC_w and ALI) used to calculate a hazard index is obvious.

11.3 The fast breeder U/Pu fuel cycle

Hazard indices were calculated for a fast breeder running on recycled plutonium and depleted uranium. In order to simplify the task, only a mixture of core and blanket elements corresponding to 1 ton of initial heavy metal was considered. An example of spent fuel data is given in Table 1. However, Figure 21 is based on a more complete set of data taken from Croff et. al. (82CRO) and shows the resulting hazard indices for discharged fuel mix and high level waste.

11.4 The accelerator driven fast Th/U breeder fuel cycle

Preliminary results from a paper to be presented at the Kalmar conference (june 1996) were used as input data. The reprocessing operation was based on a THOREX process

optimized to recover thorium, uranium and plutonium. However, this scheme leads to a major loss of protactinium to the HLW stream. The resulting hazard indices are shown in Figure 22.

12. SOME GENERAL COMMENTS AND CONCLUSIONS

An interesting aspect of this treatise is that no one ever doubts that the nuclear waste is highly hazardous due to its content of radiotoxic elements (nuclides), the term radiotoxicity being used for grouping chemical toxicity and radioactive radiation risks together. It is also commonly accepted that the only place to dispose of this material is deep in the ground, usually the bedrock. However, minerals in the ground contain the same elements, except for promethium, technetium and the transuranium elements. If toxicities of the metals within the envelop of a waste repository are compared with the toxicity of the waste elements, there is no dramatic difference between these two groups (77COH). Also, if the radiotoxicity of the host rock (due to K, Th and U) and the nuclear waste is compared, again there is no significant differences between the two. Nevertheless, the nuclear repository is considered highly dangerous, which requires extreme safety precautions, while the bedrock does not worry anyone (except in volcanic regions). This may be explained by the belief that the nuclear waste is highly labile and easily migrates to areas which use the groundwater for consumption, while the native rock binds the natural hazardous metals in immobile mineral compounds. This would be true if not the nuclear industry had designed waste containers of equal stability as the rock. In a comparison of risks of nuclear waste with radionuclides in nature, i.e. uranium ore, it is imperative to explain and demonstrate the rigor of the containment of the waste to the public.

The public is aware of releases of radioactivity from uranium ores to water (radium wells) and to the air (radon contamination of buildings). While radium wells, and also radon inhalation treatments, are considered beneficial for certain diseases (at least in some parts of the world), high levels of radon exposure in buildings in Sweden and some other countries are considered as hazardous.

In general we believe that any absolute or relative hazard index should be based on the best possible radiological and metabolical data and that we should regard ingestion as the main pathway into the body. This means that we, at present, recommend ALI(ingestion) as the base for any relative or absolute hazard index. The other bases for hazard indices are included in order to illustrate the changes which have occurred over time and to facilitate the interpretation of literature. An ALI-based hazard index is directly proportional to a similar hazard index based on the specific radiation dose to man after consumption of the waste (Sv/Bq). In case of an absolute hazard index, these two systems differ by a constant factor which is proportional to the number of Sievert generated by the continuous consumption of one ALI per year (at present 0.05 Sv/ALI) and the exposure time assumed when determining the ALI-value (at present 50 years). When a relative hazard index is used this difference disappears.

In case the waste repository can be demonstrated to have a similar stability against releases to the environment as a natural uranium ore body, and the hazard from depleted uranium is not considered, a hazard reference system based on uranium ore (NOreHirs) is the obvious choice. This choice of reference system leads to a change in the hazard scale, but the shape of any curve does not differ from that in a graph of the corresponding absolute hazard index. In some underground mining operations, e.g. Olympic Dam Operations (Australia), the mine refuse is mixed with cement and backfilled into empty mining caverns as a type of concrete and thus approaches the original ore in inaccessibility. However, one might argue that the mine refuse from other mining and leaching operations is deposited in a much less stable form than the original ore and is much more accessible to weathering. In such cases a sum of the corresponding NOreHirs and MRHirs is a possible reference system. This reference varies

with time and hence the relative hazard index graphs have curve shapes that differ from than the corresponding absolute hazard index. Alternatively one might regard the hazard from the mining refuse as additional to the hazard from a repository and thus add MRHirs to the hazard from the repository instead of to the reference system. One might also include the hazard from the depleted uranium, either in the reference hazard system or in the hazard from the waste. However, as depleted uranium is a material mainly used outside the nuclear energy field we feel that it should not be included in normal hazard calculations for nuclear energy waste.

If we regard a case where the mine refuse and depleted uranium is deposited in geologic formations with properties comparable to a high level waste repository it can be argued that the proper reference hazard should be the amount of uranium (with daughters) eliminated by fission or transmutation to higher actinides during reactor operation. The relative hazard is then shifted by a constant factor like in the case when natural uranium ore is used as reference.

A relative hazard index based on the absolute hazard from unused fuel is hard to defend and is not recommended, although it has been mentioned recently (e.g. 96IAEA).

The main difference in the time variation of absolute and relative hazard indices found in the literature is due to the use of the number of MPC_w, 10CFR20 limits or ALI(ingestion) as a measure of hazard. The main reason is the numerical changes illustrated in Tables 3 and 4. A complete survey is given in appendix A.

The changes made from MPC_w to ALI(ingestion) have the general effect of reducing the hazard from natural uranium ore and at the same time increasing the hazard from all actinides. For the absolute hazard index the effect of the changes is well illustrated for spent PWR fuel in Figure 20. It should specially be noted that the newer ALI based hazard index for spent fuel is lower than that of the older MPC_w based index for times below about 70 years and above about 6×10^6 years. Between these times the ALI based hazard is higher, reaching a maximum of about 25 times higher around 500 years. Similarly, Figure 16 illustrates the differences in the time dependence of the relative natural uranium ore based hazard index due to the same choices of limiting data. As this Figure shows, there is only a small difference between the MPC_w and the ALI(ingestion) based relative hazard index at times below about 50 years. However, beyond 10 years the ratio between these indices grows to a maximum of about 25 at about 500 years and then decreases slowly again to reach one somewhere beyond 10^8 years.

Effects of a type similar to those described above also occur for other fuel types and fuel cycles as illustrated in Figures 19, 21, 22.

A general problem with any absolute hazard index, which involves limits of consumption or breathing of contaminated water, food or air, is that it might convey the erroneous impression that nuclear waste easily reaches the environment in dangerous concentrations.

As a final summary of our conclusions, we recommend the use of relative hazard indexes. Any relative hazard index used should be based on the newest available ICRP data and recommendations and consider ingestion as the main pathway into the body. A good reference system is, in our opinion, the natural uranium present in the rock in the same volume as a repository. When used with the total repository inventory this choice avoids the problem of selecting a suitable uranium reference ore. If a more conservative reference system is desired, we recommend the amount of natural uranium ore which contains the same amount of uranium as that fissioned and transmuted during the reactor operation which generated the waste. These reference systems only differ by a constant factor and the shape of all potential hazard curves will, in the usual log-log scale, be the same for both alternatives as well as for any other choice of a reference uranium ore.

13. LITERATURE REVIEW AND REFERENCES

(Some references include brief reviews and comments on risk terminology, threshold values and dose-effect relationships. ICRP and UNSCEAR reports appear separately at the end of the list.)

31WIN H Wintz, W Rump, *Protective measures against dangers resulting from the use of radium, roentgen and ultra-violet rays*. League of Nations Publications, III Health, C.H. 1054, 1931.

Authors use the reddening of skin after X-ray exposure as a reference for radiation damage. Two contradictory opinions are presented: 1) a *tolerance dose* exists, which does not produce any discernable effect; 2) all doses, even those below the tolerance one, are harmful, because at whatever low intensity the energy of the radiation is enough to cause biological cell damage.

The tolerance dose for skin irradiation by X-rays is given as 4000 R/annum. An X-ray dose rate of 1/3 10-5 r/sec for 8 hour day during 300 working days per year yields a dose of 29 R/year, which "could be held to be harmless with absolute certainty". They call this an *admissible dose*. They also express the opinion that "the cell is able to deal rapidly with the energy of small amounts of X-rays" and that "much of the radiation taken up in the body is wholly without biological effect".

51COR C D Coryell, N Sugerman (Eds.) *Radiochemical studies. The fission products.* McGraw Hill Book Co, New York 1951.

This is the first detailed publication (except for the US AEC Declassified Documents) on fission product composition.

53MOT J Moteff, Report General Electric Co, USA, APEX-134, 1953. In PRO56.

53NCRP United States National Committee on Radiation Protection, *Maximum permissible amounts of radioisotopes in the human body and maximum permissible concentrations in air and water*, NBS handbook 52, Washington D.C. 1953.

Gives Radiation Concentration Guide (RCG) values according to 10CFR20 (Code of Federal Regulations).

55LOC J C Lock, AERE Report C/R 1715, Harwell 1955. In PRO56.

56PRO Appendix III in Progress in Nuclear Chemistry, Vol. III, *Process Chemistry*, Vol. 1, Pergamon Press, London 1956.

First comprehensive description of the back-end of the nuclear fuel cycle.

58BRU A M Brues, *Critique of the Linear Theory of Carcinogenesis*, Science, 128 (1958) 693.

Early biomedical criticism of the linear dose-effect correlation suggested to be used by the ICRP.

58PRA J Prawitz, J Rydberg, Acta Chem. Scand., 12 (1958) 369, 377.

Detailed (calculated) nuclide and *elemental* decay curves.

71BEL M J Bell, R S Dillon, *The Long-Term Hazard of Radioactive Wastes Produced by the Enriched Uranium, Pu-238U and 233U-Th Fuel Cycles*, USAEC Oak Ridge ORNL-TM-3548, 1971.

The tree different fuel cycles all refer to fuel initially with 3.3% enriched uranium and a burn-up of 33,000 MWd/ton heavy metal (HM) at 30 MW/ton in (i) a LWR, (ii) a LMFBR and (iii) a molten salt thorium-U breeder. The waste is divided in high-level (fission products FP) and Alpha (trans-lead TL). Calculations are for 460 FP and 80 TL isotopes and cover 10^7 y. Three ways of comparisons are made:

a) For each nuclide a "dilution volume" is calculated; the radioactivity is divided by the Radiation Concentration Guide (RCG) value for unlimited water consumption according to 10CFR20 (CFR = Code of Federal Regulations). For LWR the risk dominates in the order ^{90}Sr, ^{241}Am, ^{243}Am, ^{239}Pu, ^{226}Ra, ^{129}I by time.

b) An ore concentration volume: The waste is thought to be deposited in 550 ton salt + 2400 ton shale, which, thus dilutes the radioactivity. The amount of U in the waste leads to a deposit with 1 ppm U, less than the crust average of 6 ppm. The amount of ^{234}U corresponds to a 15 ppm U-deposit. Etc. The results differ with the fuel cycle chosen. Also a comparison is made with the dilution volume necessary for making the salt deposit drinkable, which turns out to be a much larger volume than needed by the RCG values.

c) A relative water volume: The dilution volume of a) is divided by the dilution volume for the ore from which the HM was produced. Results: Water volume at 1000 y is smaller for high-level waste than for ore tailings. At 10 000 y the An waste is about as dangerous as the ore tailings.

References:

D E Fergusson et al., *Chem. techn. Div., Ann. Progr. Report*, ORNL-4422 (p.69) 1969.
F L Culler, J O Blomeke, W G Belter, *Current Development in Long-Term Radioactive Waste Management*, Peaceful uses of Atomic Energy, Geneva 1971, 49/P839.
M J Bell, *Heavy Element Composition of Spent Power Reactor Fuels*, ORNL-TM-2897, 1970.
M J Bell, *ORIGEN - The ORNL Isotope Generation and Decay Code*, ORNL-4628, 1971.

71GER *Hazard potential of radioactive waste*, Proc. Int. Conf. Radioecology applied to the protection of man and his environment, EUR-800, Rome 1971.

72CLA H C Clairborne, *Neutron-Induced Transformation of High-Level Radioactive Waste*, USAEC Report ORNL-TM-3964, Oak Ridge 1972.

The effect of n-irradiation and reprocessing is analyzed for all heavy actinides. Risk will dominate in turn from Am, Cm (1000 to 10 000 y) and Np at 100 000 y. Recycling will reduce risk by factors 5 to 250 depending on efficiency in chemical steps.

"The controlling consideration of hazard from the viewpoint of long-term storage or disposal of radioactive materials is the danger of their dissolution or dispersal in underground waters with subsequent ingestion by human beings. Consequently, a good measure of ingestion hazard associated with a mixture of radionuclides of widely varying activities is the quantity of water required to dilute the radioactive mixture to a concentration low enough to permit unrestricted use of the water; the larger the amounts of water required, the greater the potential hazard. The hazard measure for the mixture is determined by summing the amount of water required to dilute each individual nuclide to its RCG-value for unrestricted use of water." [The reviewer wonders if the conclusions is that in the case that the radionuclide solubility is lower then the RCG-value, would it then be harmless independent of its total radioactivity?]

Report gives a number of plots of Hazard index: Volume of water/Volume of waste or ore, versus Age of waste, for various reprocessing and recycling schemes. In these figures horizontal reference lines are given for 1) Pitchblende containing 60% U, 2) Typical uranium ore (0.2% U). The calculations and diagrams are very similar to those in 95CHO.

Reference is made to a report by F Gera and D J Jacobs, "Hazard potential of Radioactive Waste", presented at an int. symp. on radioecology in Rome in Sept. 1971 (paper 44).

72ELK J Elkert et al., *BEGAFIP - Ett program för beräkning av klyvningsprodukternas aktivitet, beta- och gammaeffekter*, AB Atomenergi, Internal report RF-72-374, 1972.

73BEL M J Bell, *ORIGEN - The ORNL Isotope Generation and Depletion Code*, ORNL-4628, May 1973.

73FRI N A Frigerio, R S Stowe, *Carcinogenic and genetic hazard from background radiation*, IAEA-SM-202/805 p. 385, Vienna 1973.

This is a fundamental and much debated investigation of the cancer frequency in 50 different US States, trying to correlate it with a great number of possible or imaginative causes. The only correlation found seems to be a slow decrease in cancer frequency with increasing natural radiation background.

73WAL G Walinder, p. 40-41 in *Kärnkraftens säkerhetsaspekter* (*Safety aspects of nuclear power*), Meeting of Environmental Protection Delegation, Dept. of Industry Oct 1973. Aktuellt i industripolitiken, Febr. 1974.

74ELO U Elowsson, Build-up of Transuranium Isotopes in HTRs, Dragon project internal report DPPN/302, October 3, 1974.

74MCG P E McGrath, *Radioactive waste management, Potentials and hazards from a risk point of view*, KFK 1992, Kernforschungszentrum Karlsruhe, June 1974.

Report summarizes volumes, concentrations and radioactivities of nuclear material in the fuel cycle (especially actinide production), evaluates the societal risk components ("design under risk", "design under uncertainty", etc), introduces a hazard index (HI) and then calculates HI-values for the wastes produced in various fuel cycles: PWR with an equilibrium U fuel cycle of 3.3% enrichment, d:o with plutonium single or double recycle (19% Pu), LMFBR fed with Pu, THTR based on 233U, and HTGR with 93% enriched fuel. It further evaluates transmutation and long-term waste storage concepts (deep space, under the ice sheet, earth's crust, etc). HI is defined acc. to

$$HI_i = Q_i \, MPC_{w,i}$$

where Q_i is the number of curies of isotope i in the waste mixture. HI_{tot} is the sum of all isotope HI_i's, the number of m^3 of water needed to dilute the radioactivity to acceptable limits. M. discusses how to deal with aerosols, biological half-life, etc., to produce a potential hazard index (PHI), but does not use it in the graphs; To compare with natural radioactivity, M. assumes that 1 ton spent fuel will yield 80 l waste glass requiring a storage "space" of 505 tons salt, and calculates (a) that 1 g U has a HI of 15.1 m^3 water, and 1 g Th 3.8 m^3, from which (b) the earth's crust with 4 ppm U and 12 ppm Th will yield a HI of 5.35×10^4, and (c) an 0.2% U ore yields a HI 1.7×10^7 m^3; in both cases for 505 tons of rock or ore; similarly for monazite sand HI = 3×10^6 and Oklo 1.14×10^9 m^3 water. To dissolve 505 tons of a salt mine to potable concentration of 500 ppm NaCl would require 1.0×10^6 m^3 water. The risk analysis further treats accident conditions (leakage, flooding, volatilization, etc).

74WASH WASH-1400 (Draft). "*Rasmussen study*". Appendix VI to Reactor Safety Study, USAEC Aug. 1974:

This report predicts the radionuclide releases for various reactor accidents, with consideration of their high-temperature chemistry. Risk analysis is made for population at selected distances in downwind direction, with cancer incidence rates (deaths per year per million man-rem) acc. to the 1972 BEIR report estimates (50-165 cancer deaths per million man-rem). Risk diagrams show Frequency of type of accident occurring versus Number of fatalities. [Summary by S Rippon, *Rasmussen study of reactor safety*, Nucl. Eng. Int., Dec. 1974, p.1001.]

75HAM J Hamstra, *Radiotoxic hazard measure for buried solid radioactive waste*, Nuclear Safety 16 (1975) 180.

75HAU H O Haug, *Anfall, Beseitigung und relative Toxizität langlebiger Spaltprodukte und Actiniden in den radioaktiven Abfällen der Kernbrennstoffzyklen*, KFK-2022, Kernforschungszentrum Karlsruhe, Nov. 1975, See also 76HAU.

Gives amount of waste in tons/year and radionuclide amounts in Ci (calculated by ORIGEN) per ton heavy metal for different fuel cycles (FBR, FBR, HTR). Wastes are classified according to origin and activity. The Hazard Measure (HM) for ingestion is defined by

$$HM = \Sigma_i \, Q_i \, / \, MZK_{w,i} \; m^3$$

where $MZK_{w,i}$ is the "Maximal Zulässige Koncentration" of the nuclide in water (59ICRP, 64ICRP). To compare with natural conditions, the list below is used.

	Activity incl. daughters (μCi)	Activity incl. daughters (Bq)	Hazard measure (m^3)
Uranium (1 g)	4.81 (4.88)	1.81×10^5	15.1
Thorium (1 g)	1.09	4.03×10^4	3.78

H. refers to 75CLA for a dimensionless hazard index, which is based on the ratio of volumes of solidified waste and of uranium ore. The hazard index is not a real measure of the risk, which must include probability of exposure. H. suggests a *relative toxicity index*, RTI, which is the ratio of the HM-value of the waste to the HM value of uranium ore; the amount of ore to be chosen is flexible (e.g. 0.2%), but should be related to the uranium in the fuel. Different fuel cycles and strategies of extensive U, Pu and An removal are discussed on the basis of RTI -merits (RTI of 0.2% U-ore equals 1)

75SVA I. Svantesson, J O Liljenzin, J Rydberg, *Kriterier för bedömning av behovet att avskilja nuklider ur det högaktiva avfallet för återföring av resten genom enkel markdeposition*, Arbetsrapport AB Atomenergi AE-DW 81, Dec. 1975 (57 s.).

The source term for radionuclides in spent reactor fuel is calculated with the BEGAFIP program (406 nuclides), including daughter nuclides. Values obtained in Ci are divided by MPC and MPBB values to yield a "hazard index", defined as the volume of water needed to dilute the radionuclide to its MPC_w value; the results are presented graphically. Alternative fuel cycles are then described: Reprocessing in which U and Pu are separated from the rest, which decays for about 10 years and is then again reprocessed by which Cs, Sr and the rest-actinides are removed. The waste from the last step is mixed with mine refuse and returned to the mine, while the actinides are returned to the fuel cycle for burning; Sr and Cs are stored or used.

Different hazard criteria are discussed:

- o the Ci amount in 1 ton spent BWR or PWR fuel.
- o the Ci amount divided by the MPC_w (or MPC_a) value to yield a "hazard index"; these values are compared with the corresponding values obtained from the uranium ore needed to produce 1 ton uranium fuel.
- o the Ci amount divided by the MPBB value;
- o the Ci amount divided by MPC_w/k_d, where k_d is the radionuclide enrichment value in nature, thus taking into account that there are process in nature which may concentrate the radionuclide;
- o the Ci amount divided by MPC_w/d, taking into account that there are processes in nature which remove the radionuclides from the groundwater;
- o a hazard index combining the last two aspects, expressed in form of a safety distance; outside this safety distance, the water can be drunken without limitations; this index is thought to be practical for selecting deposition places.

76GUI B Guillaume, *Problémes poses par la présence d'éléments transuraniens dans les déchets du retraitment des combustibles nucléaires*, B.I.S.T., C.E.A. No. 217, Sept. 1976, p.33.

Composition of actinides in waste from different reactors. A characteristic hazard index is calculated to evaluate removal of actinides from HAW to make it "bearable". For comparison CMAP (Concentration Maximale admissible dans l'air ou l'eau de boisson pour le public; i.e. MPC) values are compared with those from (i) 4000 ton 0.25% U-mineral, (ii) waste glass, (iii) 1 m^3 mineral with 0.25% U. A suitable solvent extraction technique for heavy actinide removal (using TBP, HDEHP, etc) is described.

76HAU H O Haug, *Some aspects and long-term problems of high-level and actinide-contaminated spent fuel reprocessing wastes from the U-Pu and Th-U fuel cycles*, In "Management of radioactive wastes from the nuclear fuel cycle", IAEA, Vienna 1976.

This is a summary of the more comprehensive original German paper 75HAU.

The *relative* toxicity is stressed, i.e. the radiotoxicity of the waste must compared with something to be comprehended by the society; the comparison chosen is radioactivity in nature, at 3 different levels:

(a) The MPC of trans-uranium nuclides in water is evaluated by comparison with the radiotoxicity of ^{226}Ra. They are based on the maximum permissible dose for ^{226}Ra to the bones as the critical organ (67ICRP#2).

(b) This concept is extended by comparing the radiotoxicity of the radionuclide mixture (incl. actinides) in solid or solidified wastes fixed in a matrix of very low solubility, with the radiotoxicity of the nuclide inventory of the same amount of low-grade uranium ore. [I.e. radiotoxicity of a weight or volume of waste is compared with that of an equal weight or volume of ore.] The radiotoxicity of naturally occurring uranium in equilibrium with its decay daughters is mainly determined by the toxicity of ^{226}Ra and its daughters.

(c) Finally, the high-level waste disposal concept is considered, which comprises the final storage of the solidified high-level waste in a single bore-hole in a deep geologic repository. The comparison is made between the radiotoxicity of the nuclide inventory of the total volume of the high-level waste disposal layer (i.e. the waste cylinders plus surrounding rock) and the radiotoxicity of the nuclide inventory of the same volume of low-grade uranium ore deposit. [Note: The radiotoxicity comparisons will depend on the physical dimensions of the waste matrix and repository!]

It is pointed out that there is a considerable resistance among scientists to accepting the cubic-meter-of-water-scale as a "radiotoxic hazard measure (71BEL/DIL) or "hazard index" (73BLO/NIC/MCC) because of possible misunderstanding. "As a useful scale for comparison of potential radiotoxic hazard, we therefore have introduced a dimensionless Relative Toxicity Index (RTI) based on the radiotoxicity of low-grade uranium ore". This ore is 0.2% in U. See Figure 10. The radiotoxicity (in m^3 water assumes that all hazardous radionuclides are

easily soluble, i.e. it is a *potential hazard*, not an actual one. As uranium and thorium ores have existed in all times, "the radiotoxicity of uranium ore deposits can therefore be considered a risk that is acceptable by man". [The dissolution of radionuclides from the waste and from the ore are assumed equal.]

A number of figures show RTI versus time for different fuel cycles. The conclusion is that, considering the total disposal layer, "after 1000 y there is no significant increase in the radiotoxicity level beyond comparable geologic formations." Actinide partitioning is not needed.

Comments by

F Gera: 0.2% U-ore cannot be considered safe, groundwater may contain hazardous concentrations of Ra.

J B Morris: If man has lived and accepted to live with uranium ores, shall we now say that God made a mistake 4000 million years ago?

R W Barnes: .... we felt that the relative toxicity approach, though helpful, did not fully cover the subject and was not easily understood by the public. The hazard to man represented by a substance is dependent on the mode of uptake and its availability to man – on its quantity, chemical form and pathway. At the present time we are working on an approach which involves comparing the hazard of spent fuel with other known chemical and biological toxins. [cf. definition of risk in §1]]

Haug (in reply): The criticisms deals with "risk analysis aspects" which are now under discussion ..... [cf. our §1].

76SOU Y Sousselier, J Pradel, O Cousin, *Le stockage a tres long terme des produits de fission*, in "Management of radioactive wastes from the nuclear fuel cycle", IAEA, Vienna 1976.

The suggested strategy for management of high-level nuclear waste is solidification (immediately after reprocessing) in a reversible process, retrieval of the products after 20-30 years, separation of transuranics (and, perhaps some noble metals), storage in geologic formation of the two waste fractions. The properties of geologic repositories is analyzed. The hazard (nuisance) of the waste is compared to that from pitchblende measured in m^3 water needed to dilute the radionuclides to the MPC_w or MPC_a value.

76VER B Verkerk, *Actinide partitioning*, in "Management of radioactive wastes from the nuclear fuel cycle", IAEA, Vienna 1976.

The need for actinide partitioning is discussed on basis of the radiotoxic hazard measure for commonly suggested disposal methods. Several radiotoxic hazard measures seem to be used: 1) The volume of water needed to dissolve the radionuclides in a given waste volume to drinkable concentrations using MPC_w-values, or corresponding MPC_air-values. [This is, of course, dependent on the physical condition of the waste (e.g. glass), but easy for natural radioactivity:] 10^8 for pitchblende with 70% U, and 10^5 for common uranium ore. 2) Calculate (i) the waste activity for a given energy production (ii) translate it into water of MPC quality, and (iii) compare it with relevant amount of radioactive ore. 3) Translate radionuclide activity into dose values (rem) which are then compared with known dose-effect relations: "The risk of the waste is considered according to the *harm* it would do if eaten or inhaled," The paper focuses on this aspect.

Using the ORIGEN code the author calculates the dose from various long-lived nuclides at 1000 y, contained in the 250 kg of glass obtained per ton fuel at a burn-up of 33 MWd/kg. 1 gram of this glass, completely ingested produces a 50 year dose of 25.4 rems, and completely inhaled a total dose of 205 000 rems. The author notes some difficulties in the practical administration; he assumes that 10% of the glass will be soluble in the body. Referring to 77COH, Verkerk uses the dose values to calculate/give the amounts in the table below, from which the number of *cancer doses* (*ingestion* or *inhalation*, i.e. having a 50% probability of causing cancer) are calculated.

Figures in μg or μCi	Reactor Pu	^{239}Pu	^{241}Am	^{243}Am	μCi
Inhalation	260	1400	25	456	86
Injection into bloodstream	78	420	7.4	137	26
Ingestion with food	2.3×10^6	12×10^6	2.1×10^5	4×10^6	7.4×10^5

Cancer-causing amounts of old waste glass are, for inhalation 0.31 g, and for ingestion 2700 g. This "risk" is compared with other risks (cadmium dust, mercury dust, etc) . A comparison is also made with the external

radiation from old waste glass; the dose rate at 1 m is 0.1 mR/h. The conclusion: old waste is not very harmful, and thus partitioning is not needed.

77COH B L Cohen, *High-level radioactive waste from light-water reactors,* Rev. Mod. Phys. 49 (1977) 1.

This is a comprehensive and widely quoted paper, which contains well described calculations of waste hazards under various conditions, particularly related to underground storage. Amount of fission products and actinides produced refer to a standard reference reactor (400 Gw_e; 30 MW/ton fuel, 33 000 MWd/ton thermal energy) calculated by the ORIGEN code. The thermal power of the waste and temperature effects in a repository are given. The hazard is subdivided into external and internal risks.

The external risk is related to the gamma power of the waste (watts). The cancer risk per rem (BEIR II, 1972) is listed and used in calculations producing *number of cancer deaths expected* from exposure of critical organ to the waste (assumed to have various geometric forms, e.g. concentrated or spread out on the surface of USA.): a random spread should be used as the ICRP#2 (BEIR, NRC, etc.) use a random cancer induction relationship. [The dose effect radiological concept is said to justify the risk comparisons made in this paper.] When all cancer risks are added together, the sum amounts to 180×10^{-6} cancer incidences per rem (BEIR II) [or 0.02 per Sv, which should be compared to the value of 0.05 in use in 1995.] Accordingly, *the risk is calculated as the number of cancer deaths expected.* After 500 y, the death rate in the US for a random spread of the nuclear waste on the US surface will amount to about 5 cancers per year, and then decreases.

The internal risk is related to the MPC-value (Maximum Permissible Concentration for occupational exposure in water and in air, MPC_w and MPC_a). The risk of expected cancer deaths from the main waste products are calculated as a function of time (after reprocessing). The risk begins at 10 y with 10^{11} cancer deaths, decreases to about 10^6 at 500 y, and to 10^5 at about 1 million years. The risk curves for ingestion and inhalation do not differ much, though different nuclides dominate.

These *cancer death risk values* are then compared with other hazardous substances produced annually in the US (inhalation: chlorine manufacturing produces 4×10^{14} lethal doses, ammonia 6×10^{12}, hydrogen cyanide 6×10^{12}, etc; for ingestion: barium 9×10^{10}, arsenic 10^{10}, etc.). These values put the nuclear waste in the same category as other hazardous products, except that the hazard of the nuclear waste decays rapidly by time. $LD_{50/30}$ values in grams are given for Se (0.35 g), KCN, $HgCl_2$, etc. and compared with the nuclear waste values of 0.03 g at 10 y, and 170 g at 500 y. Comparison is also made with natural radioactivity in the US soil, which contains 3×10^{13} cancer doses of ^{226}Ra.

The paper considers various release scenarios for the waste nuclides. Various kinds of intrusion in, control of, etc., the waste repository are also discussed.

For the hazard from the mill tailings (of 400 GW), neglecting Rn, the ingestion hazard (in cancer doses) surpass the hazard from the reactor waste after 250 y, while the inhalation hazard of the tailings is less than that from the reactor waste up to about 10 000 y. As the mill tailings are less securely buried, the author concludes that they represent a far larger potential hazard than the reactor waste.

The calculations yield a number of interesting results:

a) U and Ra are equally leached into groundwater from US soil/rock; at a rate of 2.5×10^{-8} per year; the leach rate for the nuclear waste will not exceed this as the waste is incorporated more "scientifically".

b) Transfer of ingested Ra to bone is only 0.2%, which is 15 times less than ICRP#2 assumes (new value in 90ICRP#60).

c) The transfer function for U and Ra in nature to bone in man is "known to be" 4×10^{-13} and 2×10^{-12}, respectively.

* LD_{50} = Lethal dose in 50% of cases; $LD_{50/30}$ = death occurring within 30 days. For calculation of internal doses: water intake of 2.2 liter/day, or 0.8 m^3/y, of air 7300 m^3/y. MPC-value would give a dose commitment of 30 rem for bone and thyroid, 15 rem for kidneys, lungs,etc. (ICRP 1959).

77ERL P R Erlich, A H Erlich, J P Holdren, *Ecoscience: Population, Resources, Environment*, W H Freeman and Co, San Fransisco 1977.

This is a well known student text and reference book in ecoscience by renown scientists, also engaged in the public debate. The nuclear waste issue is discussed on p. 579ff in connection with cancer risks.

77KAT R W Kates, *Assessing the Assessors: The art and ideology of risk assessment*, Ambio 6 (1977) 247.

77KJE N Kjellbert, *Källstyrkor i utbränt bränsle och högaktivt avfall från en PWR beräknade med ORIGEN*, KBS TR 01, Kärnbränslesäkerhet, Stockholm 1977.

78ADA N Adams, B W Hunt, J A Reissland, *Annual Limits of Intake of Radionuclides for Workers*, NRPB-R82, Harwell, Oct. 1978.

Suggests the use of ALI(x), where x is the effective yearly whole body dose equivalent in Sv (e.g. ALI(0.05) for a limit of 0.05 Sv/year) in order to differentiate future ALI values based on different yearly dose equivalents. This report uses the methods later applied in 90ICRP#60.

78COH J J Cohen (LLNL, USA), *Why partition nuclear waste?*, in "The Management of Radioactive Waste: Waste Partitioning as an Alternative", US Nucl. Regl. Comm. NR-CONF-001, 1976.

This paper discusses the hazards criteria needed for choosing a waste partition strategy. Partitioning is defined as a process where the high-level waste is subdivided into two fractions, both being waste but with significant differences. Partitioning is not exhaustive reprocessing to recover 99.95% of U and Pu, nor the extraction of some valuable products contained in the HLW. Partitioning is justified when the costs and risks of the separated components is less than those for management of the initial HLW. Assuming that management costs are approximately the same for both sides of the equation, the significant point will be whether the risk (in handling and to the public) can be reduced through partitioning or not (by segregating the long-term/half-lives nuclides). C. calculates an annual ^{239}Pu production of 10^7 g, corresponding to 30×10^6 "lethal doses"; the Pu lethal dose is given as 0.4 g via ingestion of soluble material. This is compared to lead; annual waste production 10% of total production, i.e. 4×10^8 g, lethal dose 10 g, number of lethal doses 4×10^7 per year. Half-life for lead is infinity. Referring to 76HAU who plots a relative hazard index versus time and compares it with natural (0.2%) U ore, and 74BON and 76COH who compare the waste risk with that of pitchblende, C. concludes that the risks from the waste are not so high that it is worth while (or needed) to undertake partitioning. Partitioning is only motivated by public relations: "the price we must pay to get public confidence in nuclear energy". C. concludes such an attitude may be counterproductive: If the public sees vast expenditures and inordinate effort, time and other resources devoted to nuclear safety, they logically conclude that nuclear energy must be extremely hazardous.

78KBS1 *Handling and final storage of unreprocessed spent nuclear fuel*, Svensk Kärnbränslesäkerhet (KBS), Stockholm 1978.

The radioactivity of the most important nuclides in of spent fuel is presented in curies per ton spent PWR fuel (c.f. Fig. 3) as a function of time after discharge up to 10^7 years (source strength and input data p. 204). Biopath calculations (including dose conversion factors, Ci to rem) leads to graphs showing dose to man (rem/year) as a function of time.

78KBS2 Handling of spent nuclear fuel and final storage of vitrified high level reprocessing waste Nuclear Fuel Safety Project 1977, Stockholm 1978.

This report is a corollary to 78KBS1 as it considers the waste from reprocessing of U-Pu fuel cycle (later to be abandoned by the Swedish Government). The treatment is more comprehensive than in KBS1. The activity of reprocessing waste is given in Ci/ton spent reactor fuel.

79COH B L Cohen, I-Sing Lee, *A catalog of risks*, Health Physics 36 (1979) 707.

Information on risks is collected from various sources and converted into *loss of life expectancy* throughout life and in various age ranges. *Risks* included are radiation, accidents of various types, various diseases, overweight, tobacco use, alcohol and drugs, coffee, saccharin, the Pill, occupational risks, socioeconomic factors, martial status, geography, war, catastrophic events, energy production and technology in general. Methods of reducing risks, priorities, etc are also discussed. Risks of natural and occupational exposure to radioactivity from the nuclear industry are compared with risks of similar competing activities.

79INH H Inhaber, *Risk with energy from conventional and nonconventional sources*, Science 30 (1979) 718.

This is a summary of a much larger paper giving a comprehensive review of the risks to human health from 11 different ways of producing energy, also taking into account the risks in producing the raw material and construction of the energy plant. The hazard is given in *loss of man-days*, occupational as well as to the public.

Environmental effects are not included. Bearing this in mind, natural gas and nuclear show lowest numbers of lost man-days, coal, oil, wind and solar the highest.

80CHO G Choppin, J Rydberg, *Nuclear and Radiochemistry*, Pergamon Press 1980.
First university text book also discussing nuclear waste issues.

80COH B L Cohen, *The cancer risk from low-level radiation*, Health Physics 39 (1980) 659.

This paper reviews the various lines of evidence leading to current estimates of the cancer risk from low-level radiation. It is shown why it is difficult to get direct evidence, and to what extent one can rely on extrapolations from high-level radiation data. It is concluded that the common dose-effect relation probably over-estimates the risk. The paper ends with the example that the radiation background increase due to nuclear power in the US corresponds to that smoking one cigarette every 20 year, or an overweight of 0.3 grams.

80CRA D J Crawford, R W Leggett, *Assessing the Risk of Exposure to Radioactivity*, Am. Sci., 68 (1980) 524.

Assessment of risk from man-made radiation requires the development of mathematical models capable of accurately describing the complex relationships existing among all pertinent physical and biological factors. The linear dose-effect relationship is totally inadequate for this purpose.

80CRO A G Croff, *ORIGEN2 – A revised and updated version of the Oak Ridge isotope generation and depletion code*, ORNL-5621, Oak Ridge 1980.
Contains also Elemental chemical toxicities.

80CRO2 A G Croff, M A Bjerke, *Revised Uranium-Plutonium Cycle PWR and BWR for the ORIGEN Computer Code*, ORNL/TM-6051, 1980.

80OLS G Olsson, P Hägglöf, S Svensson, *BEGAFIP. Programvård utveckling och bench-markberäkningar*, SKBF/KBS Technical report 80-20, Oct. 1980.

81BEN M Benedict, T H Pigford, H W Levi, *Nuclear Chemical Engineering*, 2nd Ed., McGraw-Hill 1981.

Although this important standard text book contains lots of data as cross sections, fission yields, decay curves, waste treatment and storage methods, waste stability, etc, there is only a brief discussion on radiation risks. The risks from radioactive waste are mainly illustrated by specific radioactivity curves or by potential hazard index curves from ORIGEN calulations, which use US RCG-data.

82CRO A G Croff, M S Liberman, G W Morrison, *Graphical and tabular summaries of decay characteristics for once through PWR, LMFBR and FFTF fuel cycle materials*, ORNL/TM-8061, Oak Ridge 1982.

7.16 MT of U must be mined to produce 1 Mton heavy metal (MT HM) in fresh fuel (10% U lost in mining, 1% in conversion, 1% during fabrication; isotope enrichment depleted stream 0.25%); this amount of ore requires 1.1×10^8 m^3 of water to dilute it to the RCG_w value (10CFR20). [The assumption of 0.25% ^{235}U in the tails stream is contradictory to the 0.20% ^{235}U used for depleted uranium in the ORIGEN2 calculations.] Diagrams show toxicity in m^3 water (of 10CFR20B value) per MT Initial HM versus time for different types of spent fuel and reactor components. In comparison, the toxicity is about the same for the three alternatives to about 100 y, after which the PWR-U reactor waste becomes about a factor 3 less toxic than FFTF or LMFBR reactor waste.

82LUC T D Luckey, *Physiological benefits from low levels of ionizing radiation*, Health Physics 43 (1982) 771.

An extensive literature search (219 references) indicates that minute doses of radiation is beneficial to animals.

83KBS *Final storage of spent fuel - KBS-3*, Swedish Nuclear Fuel Supply Co, Stockholm 1983.

This continuation of 78KBS presents the waste risk in the form of Bq/ton spent fuel (PWR 38 000 MWd/tU, 38.5 MW/tU and orig. enrichment 3.2% 235U) and total induced radioactivity (Bq of 25 000 fuel boxes and 204 boron glass rod bundles).

84ANS *Report on the special committee on source terms*, Am. Nucl. Soc., Sept 1984.

Gives inventory of different reactor cores and releases of various nuclides (judged on their chemistry) in case of reactor accident. No calculation of doses to the environment.

85ADL M Adler, *Ten philosophical mistakes,* McMillan 1985.

85YAL R S Yalow, *Biological effects of low-level ionizing radiation*, United States Environmental Protection Agency EPA/600/M-85/009, 1985.

A Nobel Prize winning biochemists stresses the lack of statistical support for the hypothesis of somatic or genetic effects of low-dose radiation.

87HEC R E Heckman, *Developing Criteria for the Management of Nuclear Waste*, Livermore Review 1987.

Report describes work for the US Department of Energy carried out at the Lawrence Livermore National Laboratory, particularly for developing a regulatory framework (regulations, standards and guides) for safe management of nuclear wastes. It presents systems analysis for risk of waste management systems by a computer simulation model. It presents the radiological risk in man x mrem/RRY, where RRY = Reference Reactor Years. One RRY equals 35 m^3 of spent fuel, or 8 m^3 of high-level waste, the amount of waste from one 1000 MWe reactor operating for 1 year. The report gives a chart showing the hazard index in m^3 of water (the volume of water the element has to be dispersed in to render it harmless, i.e. make the water permitted to drink) versus age of waste of spent fuel from one RRY compared to hazards from an equal volume of average ores of common toxic elements. These elements are, in decreasing hazard, mercury, pitchblende, chromium, selenium, lead, cadmium, silver, barium arsenic and uranium; at 1000 y the fission products hazard and the plutonium hazard go below the cadmium (and Pb, Se, Cr, Hg) level.

88HES U Hesse, *OREST – The HAMMER-ORIGEN Burnup Program System: Method and Results*, Nucl. Technol. 82 (1988) 173.

89LIN B Lindell, L Sjöberg, (a) *Vilket är viktigast vid riskbedömning: sannolikhet eller konsekvens?*, Läkartidningen 86(1989)4435; (b) *Översikt om riskjämförelser*, ibid p. 4525.

89SRI M Srinivasan, K Subba Rao, M V Dingankar, *Special actinide nuclides: fuel or waste?*, in J W Behrens and A. D. Carlson (Eds.), "50 Years with Nuclear Fission", Am. Nucl. Soc., Illinois 1989, p. 799.

90BER U Bergström, S Nordlinder, *Dose conversion factors for major nuclides within high level waste*, SKB Techn. Report 90-35, Stockholm 1990.

90LIL J O Liljenzin, *Some estimates of the total nuclide inventory in the year 2100 from Swedish nuclear power production*, SKI Techn. Report 90:18, Stockholm 1990.

90SON C A Sondhaus, V P Bond, L E Feinendegen, *Cell-oriented alternatives to dose, quality factor, and dose equivalent for low-level radiation*, Health Physics 59 (1990) 35.

Paper analyses ionization densities in tissue cells for different radiation sources, and concludes that the simple linear dose-effect relation of radiation damage to the cell is not applicable for low level irradiation.

91BEN B G Bennet, *Environmental consequences of radionuclide releases*, in Vol. I, 91SSI, p.245.

Presents annual doses from natural radiation sources, nuclear explosions and accidents. From the releases in Bq, dose conversion factors are used which take into account environmental and biological pathways, e.g. ^{137}Cs from nuclear power production is assigned a normalized collective effective dose of 5000 man Sv per PBq. The paper contains a statement that "through 1985" there have been approximately 6000 cancer deaths in this population" (76 000 atomic bomb survivors in Japan) and that "it has been determined that there has been only 80 radiation-induced leukemia and 260 radiation induced solid cancers (8). A significant observation is that radiation induced cancers continue to occur." Reference (8) is to an IAEA report on Chernobyl. [The reviewers are confused by this information, which does not seem in line with another observations.]

91BEN2 S Benassi, P Paris, *A unified methodology for evaluating safe disposal of radioactive wastes*, in Vol. I, 91SSI, p. 393.

According to Italian regulations, two risk concepts are used: (i) maximum admissible concentration in drinking water (e.g. 1 μg Hg/l) and (ii) maximum admissible concentration in liquid effluents (e.g. 5 μg Hg/l). Using daily intake values of water, and food by ICRP#23 (Standard man) the mean daily intake falls between these two restrictions. It is pointed out that the natural background is spread among very different values (e.g. for Hg from 0.002 to 40 μg/l). For radionuclides, the acceptable concentration (AC) is derived as AC = ALI/ (2x365x500) where ALI is referred to a committed dose of 5 mSv/y. A unified approach for radioactive and toxic substances are needed to develop a coherent and common evaluation of real risks associated with radioactive and toxic substances.

91CRU F Diaz de la Cruz, *ICRP Dose Limits: a Dissenting View*, Nuclear Europe World Scan 7-8, 1991, p.64.

91HÖG L Högberg, *Swedish Nuclear Power Inspectorate*, 05.02.91.

91MER E R Mertz, *Lessons to be learned from radioactive waste disposal practices for non-radioactive hazardous waste management*, in Vol. I, 91SSI p. 85.

In establishing criteria for radioactive and chemotoxic wastes the same principles must be used. This is needed for regulatory requirements and international comparisons. The overall health risk can be determined by the formula

$$HR = Q\ T\ A$$

where HR = Overall health risk (illness, death), Q = Quantity of chemotoxic or radioactive material, T toxicity/hazard of material per unit quantity, A = access factor (fraction of substance transported from storage to man). Toxicity can be defined in several ways: ALI-values, MPC_w, etc.

Hazard measures for chemotoxic waste, HM_{ct},to be stored together with radioactive waste on a comparable basis, calculated by

$$HM_{ct} = Q_s / MPC_s$$

where Q_s = Quantity of element S in waste, and MPC_s = Maximum Permissible Concentration for chemotoxic element in drinking water.

91MOL B Molholt, *There is no 10^{-6} risk from nongenotoxic carcinogens*, in Vol. II of 91SSI, p. 103.

This is a report of biomedical studies on toxic substances. The author summarizes his findings thus: According the US EPA's "simplistic" linearized multistage model "the carcinogenic risk is directly proportional to dose all the way from studies in which the measured response is greater than 10% (>0.1) down through infinity". M. shows that most genotoxic carcinogens fail to elicit any cellular responses at 0.1% maximally toxic doses. Instead there "are threshold doses below which promotion and/or immunosuppression fail to occur. These threshold doses should be clearly defined and become the basis for regulatory standards" ....."rather than some imaginary dose corresponding to 10^{-6} to 10^{-4} cancer risk".

91SESEE *Senior Expert Symposium on Electricity and the Environment*, Helsinki 1991, IAEA 1991.

This Report contains risk comparisons of different modes of producing electricity.

91SSI *Environmental Consequences of hazardous waste disposal*, Joint Int. Symp. arranged by Swedish Radiation protection Institute, Ministry of the Environment Ds 1991:57, Stockholm 1991

91SUZ A Suzuki, *A more acceptable high-level waste*, Vol. II of 91SSI, p.113.

This is a very thoughtful paper, in which S. stresses the need to seek technological solutions to provide peace-of-mind to the public, as the current focus on very long-term storage and multi barrier systems in geologic repositories tells the public that the waste is extremely hazardous. S. proposes two ways: (i) Removal of 99% of the waste actinides from the HLW will lead to "natural uranium ore" risk level in 1000 y; the actinides should be stored for future use in reactors (LWR or FBR); (ii) omit use of dose values at <0.1 mSv/y as the effects of so low doses are "below the limit in estimating probability of risk". The risk to compare with is the radioactive inventory of a whole repository with that of natural uranium ore, or the leakage of radioactivity from such a repository with the leakage from a uranium ore deposit. He warns against the "conservatively hypothetical assumption made in estimating risk at low doses" or "scenarios far in the future", which both "multiply the public's fear of HLW".

94GON A J González, *Biological effects of low doses of ionizing radiation: A fuller picture*, IAEA Bulletin 4/194, p.37.

94HUB P. Hubert, *Management of radiation risks*, presented at the IAEA meeting on "Radiation and Society: Comprehending Radiation Risk", Paris Oct. 1994.

Risk is here defined as the probability to die in a radiological accident. Risk management must be preceded by risk assessment in 3 steps:

1) hazard identification,
2) dose response assessment,
3) exposure assessment.

In risk management the advantages and disadvantages of risk reduction should be balanced. No zero risk is achievable. A common (basic?) hypothesis is also the absence of a threshold dose.

Several risk levels can be established:

intolerable (5 deaths per 100 000; regulatory limits),
tolerable if ... (optimization acc. to the ALARA principle),
broadly acceptable (one death per million; no action)

The limits are set by the ICRP dose recommendations. The use of collective dose is sometimes felt to be an inadequate criterion. The probability and the consequence of the accidents must be handled together in one risk concept.

95CHO G Choppin, J O Liljenzin, J Rydberg, *Radiochemistry and Nuclear Chemistry*, Butterworth-Heinemann 1995.

95KAN KANE & HILL, *Comparison of waste toxicity index and repository performance assessment approaches to providing guidance for R&D on partitioning and transmutation*, European Commission contract ETNU-93-0111, Horsham, West Sussex 1995.

K&H review work on nuclear waste and possible partitioning, and discusses ways to asses benefits or risks. [We think this paper is a very important contribution to the waste analysis and therefore review it in some detail, selecting what seems relevant to our report.]

Abbr.: R&D research and development, P&T partition and transmutation, TI toxicity index ("intrinsic radiotoxicity"), PA performance assessment ("processes and events which might lead to release of waste constituents from repository and their transport to and through the human environment"). [The PA and TI definitions correspond to eqn. (1) in our report, i.e. Probability of occurrence and Consequence, the product of which is defined as the "Risk"]. K&H claim that at present stage R&D on geologic disposal is not fully comprehensive. [A statement which may be based on insufficient information.] Further, K&H claim that either the TI or the PA approach may be suitable for guidance regarding R&D for P&T, and that both criteria shall be compared, but that it can only be done qualitatively. In principle, K&H use the TI evaluation to present the "source term" hazard (the waste in the closed repository), and the PA evaluation as a transport-risk model of the toxicity from the repository to man. The most hazardous radionuclides obtained from the TI analyses may become

unimportant in the PA analyses. "The waste toxicity (as measured by TI) is not closely related to repository post-closure risk."

Two types of TI's are considered: MPC or ALI ("TIunits"), or these divided by a reference (such as uranium ore) giving a dimensionless number ("TIratio").

The conclusion of the analysis (102 pages) is that neither the TI nor the PA approach can presently be used for R&D guidance. The PA approach is preferred, because "PA results can, and will, be used in decisions on implementation of P&T", but the TI approach is also needed as guidance regarding effects (e.g. domination, or need for removal) of specific nuclides. For example, with TIratio one can calculate the time t_1 when the waste becomes equally hazardous as the uranium ore, whereas by P&T it becomes equally hazardous at time t_2, where $t_2 < t_1$. Thus TIratios are better for quantitative application to P&T than TIunits. Another advantage of TIratio is that it may be associated with some assumption that the reference material is a tolerable risk (e.g. a uranium ore); however, some groups of society may not accept this (ore) as tolerable.

K&H argue against TI-values based on total or specific activity (see Table 1) and recommend those based on ALI or MPC_w (not DAC or MPC_a as that is a less likely path to man for geologic repositories); K&H choose ALI's, as MPC's are no longer used by ICRP. However, as ALI's are regularly revised, there is presently no complete best set of ALI-values available. K&H also note inconsistencies between ALI-values and dose calculations. Therefore K&H recommend the use of dose (sieverts) as risk index, calculated for each nuclide from the activity in Bq and the conversion factors (Sv/Bq).

K&H suggest an integrated radiological toxic potential (ITP) defined by

$$ITP\ (m^3\ y) = C\ A_0\ DPUI\ \lambda^{-1}\ \exp(-\lambda t_{gw})$$

where C (m^3/Sv) is a numerical factor (identical for all radionuclides) derived from annual individual intake of drinking water and the dose limit or constraint, A_0 (Bq) is the activity of the radionuclide in 1 m^3 waste at time of disposal, DPUI (Sv/Bq) is the Dose Per Unit Intake [i.e. conversion factor] of the radionuclide by ingestion, λ (1/y) is the radionuclide decay constant and t_{gw} (y) is the groundwater return time. ITP has some advantages, but is not used anywhere.

A TI analysis is carried out for storage of HLW in clay or granite, and for spent fuel elements in granite. The report then (p. 18-56) focuses on PAGIS (Performance Assessment of Geological Isolation Systems) analyses (for HLW glass in clay {at Mol and Harwell} and granite {at Auriat in France}, and spent fuel elements by SKB-91 and KBS-3, and Project Gewähr 1985), which all give the time-dependent individual risk as dose in Sv/y, and (p. 57-103) on comparison between TI and PA analysis. [The PA analysis is outside the scope of this report.]

In the final analysis K&H conclude that while the PA-analysis will be site dependent, so is not the case with the TI-analysis. Because the public will require some international agreement on the risk analysis, the TI-analysis will be the prime choice, even though .."it can be argued that the (TI) approaches are inconsistent with the whole rational for disposal of radioactive waste in geologic repositories". [Our comment: All waste should primarily be analyzed in TI's ("universality"), perhaps for international comparisons (but will not vary much between different LWR plants), while the waste repository must be PA-analyzed nationally ("non-universality", but preferably according to some international standard)]. The values upon which TI is based (ALI, etc.) are rather conservative and stable, but some adjustments have occurred, as e.g. listed in Table 6.1 below.

Table 6.1. Relative toxicities of various radionuclides. For the purpose of illustration, ALI and DPUI values have been chosen so as to maximize the differences between radionuclides (95KAN).

	Basis for radiotoxicity estimate			
Radionuclide	MPAI 1959 -77 Note 1	ALI, EC -rules 1977-90; 1984 Note 2	DPUI 1987 Note 3	DPUI 1991 Note 4
^{238}U	1	1	1	1
^{238}Pu	0.13	2.5	15	16
^{237}Np	0.25	170	180	47
^{241}Am	0.13	10	79	43
^{244}Cm	0.083	56	44	10
^{99}Tc	0.0025	0.0050	0.0056	0.0190

1) MPAI= Maximum Permissible Annual Intake by ingestion, acc. to 59ICRP#2 to 77ICRP#6, 84CEC, 87NRPB, 91PHI.

2) ALI= Annual Limits of Intake by ingestion, 79ICRP#30 and on; EC Basic Safety Standards.

3) DPUI=Dose per Unit Intake by Ingestion; UK National Radiation Protection Board (NRPB) GS7, 1987, and 79ICRP#30 to 90ICRP#61.
4) Acc. to 90ICRP#61 and NRPB R245, 1991.

What else can affect the TI-analysis in the future? K&H conclude it could be improvements in treatment of cancer, which could to a less or a large extent affect the risk perception of the dose value (e.g. if "lethal dose" is increased from 20 to 100 Sv); K&H conclude that it may not be right to capitalize upon such a development now.

K&H also comment upon the common time-scale used with regard to nuclear waste "Hazardous for millions of years"): "In view of the long timescales involved in safety assessment of geologic repositories, it is not feasible to calculate risks to real people. There is no scientific basis for predicting human behavior and characteristics over million of years".

The advantages and disadvantages of the TI and PA analyses are summarized in Table 8.1.

Table 8.1 Summary of advantages and disadvantages of TI and PA approaches (95KAN).

Attribute of approach	Toxicity index approach	Performance assessment approach	
		Use of pre-existing PA's	New PA to guide P&T and R&D
Calculational simplicity/complexity	Simple - *advantage*	Not very simple - *disadvantage* (not large)	Complex - *disadvantage* (large)
Input data requirements	Low - *advantage*	Low - *disadvantage*	High - *disadvantage (perhaps large)*
Availability	Widely available - *advantage*	Fairly available - *slight disadvantage*	Very limited availability - *disadvantage (large)*
Presentational aspects	Transparent - *advantage*	Not transparent - *disadvantage*	Not transparent - *disadvantage*
Universality	Independent of repository site and design - *advantage*	Somewhat dependent on repository site and design - *disadvantage*	Could be dependent on repository site and design - *disadvantage*
Stability to more knowledge: - conceptual basis	Stable - *advantage*	Not very stable - *disadvantage*	Not very stable - *disadvantage*
- data and models	No advantage or disadvantage	Not very stable - *disadvantage*	Not very stable - *disadvantage*
Relationship to disposal risks	Not very closely related - *disadvantage*	Fairly closely related - *advantage*	Closely related - *advantage*
Consistency with disposal rationale	Somewhat inconsistent - *disadvantage*	Consistent - *advantage*	Consistent - *advantage*
Relative/absolute risk basis	Relative risk basis - *disadvantage*	Almost absolute risk basis - *advantage*	Absolute risk basis - *advantage*

95MUC J Muckerheide, *The health-effects of low-level radiation: Science, data, and corrective action*, Nuclear News September 1995, p.26.

95ORN *Estimating externalities of the nuclear fuel cycle*, Oak Ridge National laboratory, Martin Marietta Energy Systems Inc, U.S. Department of Energy, April 1995.

95SKB *SR95 Mall för säkerhetsrapporter med beskrivande exempel*, Svensk Kärnbränlslehantering AB, Stockholm, December 1995.

P. 5-18 covers safety goals and acceptance criteria for handling radioactive waste.

The acceptance of a waste repository shall be based on the radiological effects, independent of national borders. The ICRP recommendations will be fundamental. For the first 10 000 y the radiation dose to the individual due to releases from the repository shall not exceed 0.1 mSv/y to an individual; each single source shall not contribute with more than 10%; the influx from alpha-emitters shall be low compared to natural alpha emitters; after 10.000 y the flow of α-emitters will dominate the risk analyses. The collective dose shall be limited to 2 manSv/y per $GW_e y$, and summed over 500 y. The releases shall be analyzed with consideration of protection of the ecosystem against eradication of species.

The risks from all steps in the fuel cycle must be considered: uranium production, isotope enrichment, fuel fabrication, nuclear energy production, recovery and handling the waste, transport and storage. The report claims that the effects on the environment will cover millions of years.

95WAL G Walinder, *Has radiation protection become a Health hazard?*, Publ. by The Swedish Nuclear Training & Safety Center, PB 1039, S-61129 Nyköping. Kärnkraftsäkerhet & Utbildning AB.

This well-known oncologists comments upon the use of the linear dose-effect concept for low-level low-rate radiation exposures, which he considers scientifically primitive and lacking scientific credibility.

96IAEA *Advanced Fuels with Reduced Actinide Generation*, Technical Committee Meeting, Vienna, 21-23 Nov. 1995, IAEA 1996, proceedings in press.

96IRPA'9 *1996 International Congress on Radiation Protection*, Vienna, April 14-19, 1996. Proceedings.

96SJÖ L Sjöberg, Svenska Dagbladet, Stockholm, February 25, 1996.

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Relevant publications of
Recommendation of the International Commission on Radiological Protection (ICRP),
Pergamon Press.

55ICRP *Recommendations of the International commission on Radiological Protection*, Brit. J. Radiol. Suppl. 6, 1955.

59ICRP#2 *Permissible Dose for Internal Radiation*, report of Committee 11, 1959:

Average internal occupational exposure shall be limited to max 5 rem/year for people > 18 years of age; max value is 1.5 rem/y for single organ, except for skin and thyroid (max 3 rem/y). Maximum permissible concentration values (MPC_w for drinking water and MPC_a for air) are listed; MPC values used during 40 hour/week will produce a maximum permissible body burden (MPBB); this will deliver a dose of max 150 rem during 30 years. The MPC values for most radionuclides produce a weekly dose of max 0.1 rem to gonads & total body, 0.6 rem to skin & thyroid, and 0.3 rem to all other soft tissues. P. 11-39 describes methods of calculating MPC_w values, taking into account physical, chemical, radiological, etc aspects of the radionuclide (values later revised). No numerical risk values are presented. Instead comparisons are made; e.g. for bone-seeking radionuclides (Sr, Rn and daughters) calculated dose values are compared with effects known from ^{226}Ra + daughters.

[This volume also appears as a separate issue of Health Physics Vol. 3, 1960 (June).]

62ICRP#6 1962. *Revision of data for ^{90}Sr and for elements U-Fm.*

66ICRP#8 *The Evaluation of Risks from Radiation*, 1966.

66ICRP#9 *Recommendations of the ICRP*, (Sept. 17, 1965), 1966.

68ICRP#10 *Evaluation of Radiation Doses to Body Tissues from Internal Contamination due to Occupational Exposure*, 1968.

72ICRP#19 *The Metabolic Compounds of Plutonium and other Actinides*, 1972.

72ICRP#20 *Alkaline Earth Metabolism in Adult Man*, 1972.

74ICRP#23 *Reference man: Anatomical, Physiological and metabolic characteristics*, 1974.

(New publication series: *Annals of the ICRP*, here abbreviated "Ann"; the same reference systems is used as above.)

77ICRP#6 Ann Vol 1, No 3, 1977. *Recommendations of the ICRP.*

77ICRP#R Ann Vol 1, No 4, 1977. *Problems involved in Developing an Index of Harm.*

79ICRP#30 Ann Vol 2, No 3/4, 1979. *Limits of Intake of Radionuclides by Workers*, Part 1.

79ICRP#30 Ann Vol 3, 1-4, 1979. *Limits of Intake of Radionuclides by Workers*, Supplement to Part 1.

80ICRP#30 Ann Vol 4, No 3/4, 1980. *Limits of Intake of Radionuclides by Workers*, Part 2.

81ICRP#30 Ann Vol 5, No 1-6, 1981. *Limits of Intake of Radionuclides by Workers*, Supplement to Part 2.

The concept of collective dose commitment shall be used, although "a unique definition of this concept is missing".

81ICRP#30 Ann Vol 6, No 2/3, 1981. *Limits of Intake of Radionuclides by Workers*, Part 3.

82ICRP#30 Ann Vol 7, No 1-3, 1982. *Limits of Intake of Radionuclides by Workers*, Supplement to Part 3.

82ICRP#30 Ann Vol 8, No 1-3, 1982. *Limits of Intake of Radionuclides by Workers*, Supplement B to Part 3.

88ICRP#30 Ann Vol 19, No 4, 1988. *Limits of Intake of Radionuclides by Workers*, Part 4.

82ICRP#30 Ann Vol 8, No 4, 1982. *Limits of Intake of Radionuclides by Workers*, Index.

80ICRP#31 Ann Vol 4, No 3/4, 1980. *Biological Effects of Inhaled Nuclides.*

84ICRP#41 Ann Vol 14, No 3, 1984. *Non-stochastic effects of Ionizing Radiation.*

85ICRP#46 Ann Vol 15, No 4, 1985. *Radiation Protection Principles for Disposal of Solid Radioactive Waste.*

86ICRP#48 Ann Vol 16, No 2/3, 1986. *The Metabolism of Plutonium and related Elements.*

90ICRP#60 Ann. Vol 21, No 1-3, 1990. *Recommendations of the International Commission on Radiation Protection.*

90ICRP#61 Ann Vol 21, No 4, 1991. *Annual Limits of Intake of Radionuclides by Workers based on the 1990 Recommendations.*

Some relevant publications from UNSCEAR (*United Nations Scientific Committee on the Effects of Atomic Radiation*) United Nations, New York.

62UNSCEAR *Report of UNSCEAR 1962, 17th Session*, Supplement No 16 (A/5216).

The term risk is not defined but seems to be applied only when risks can be quantified. Risk mainly refers to the genetic and carcinogenic (mainly leukemia and bone tumors) effects, which have been most extensively studied. As the knowledge is insufficient for quantification, the concept of relative risk is developed; this is the risk relative to that from natural background radiation, which is arbitrarily set at 1. Thus, if the natural background gives rise to a dose of 200 mrem, and an artificial source (e.g. fallout) to 1000 mrem, then the relative risk from the artificial source is set as 5 (i.e. times higher than the effect of the background radiation). Comparisons can (and should) only be made between comparable effects. Thus "no comparison can be made between somatic and hereditary risks, nor between risks of leukemias and of bone tumors" (p. 30)..... "Since man has been exposed to natural radiation at an approximately constant rate, natural sources will here be taken as the reference standard on which to base comparisons with other sources" (p.29).

Quantification of risk can only be made by a dose-effect relationship, with numerically known values on the axes. However, "The deficiencies in our knowledge of dose effect relationships should be emphasized" (p.29). But "No alternative hypothesis regarding the relationship between dose and frequency of induction of malignant changes is, however, indicated in the presence state of our knowledge, and proportionality at low doses will therefore be assumed for the purpose of calculation" (underlined by us). It is stated repeatedly that a linear relationship between dose and genetic changes has been observed, but without always making the reservation that the observations relate to animal tests and doses > ca. 100 rem (the results down too about 10 rem for the fruit fly seems not altogether certain).

The concept of dose commitment is introduced to estimate the risks of nuclear weapons testing and defined as the total dose from radioactive material initially injected into the atmosphere to be received by the population in all future.

64UNSCEAR *Report of the United Nations Scientific Committee on the Effects of Atomic Radiation 1964, 19th Session,* Supplement No 14 (A/5814).

66UNSCEAR *Report of the United Nations Scientific Committee on the Effects of Atomic Radiation 1966, 21th Session,* Supplement No 14 (A/6314).

69UNSCEAR *Report of the United Nations Scientific Committee on the Effects of Atomic Radiation 1969, 24th Session,* Supplement No 13 (A/7613).

72UNSCEAR a. *Ionizing Radiation: Levels and Effects*. Vol. I: Levels,. b. ibid. Vol. II: *Effects*, United Nations, New York, 1972.

77UNSCEAR *Sources and Effects of Ionizing Radiation*, UNSCEAR 1977 report to the General Assembly. UN Publ. Sales No E.77.IX.1.

82UNSCEAR *Ionizing Radiation: Sources and Biological Effects*, UNSCEAR 1982 report to the General Assembly. UN Publ. Sales No E.82.IX.8 (06300P).

86UNSCEAR *Genetic and Somatic Effects of Ionizing Radiation*, UNSCEAR 1986 report to the General Assembly. UN Publ. Sales No E.86.IX.9 (004800P).

88UNSCEAR *Sources, Effects and Risks of Ionizing Radiation*, UNSCEAR 1988 report to the General Assembly. UN Publ. Sales No E.88.IX.7 (0900P).

93UNSCEAR *Sources and Effects of Ionizing Radiation*, UNSCEAR 1993 report to the General Assembly, with Scientific Annexes. UN Publ. Sales No E.94.IX.2.

Table 1. Composition of fuel from various reactors 1 year after unloading (except HTGR where data are for freshly unloaded fuel) in grams/ton initial heavy metal. Only selected nuclides with some importance for the hazard from spent fuel are given.

	BWR	PWR	PWR	LMFBR	LMFBR	HTGR	THTR
MWd/t	53	34	34	34	34	65	65
Fuel etc	3.6%	3.3%	MOX	LWR Pu	FBR Pu	^{233}U	^{233}U
^{90}Sr	6.66E+02	5.48E+02	4.90E+02	3.21E+02	3.27E+02	1.45E+03	1.41E+03
^{137}Cs	1.37E+03	1.23E+03	1.24E+03	1.30E+03	1.31E+03	2.41E+03	2.35E+03
^{129}I	2.43E+02	2.36E+02	2.53E+02	2.19E+02	2.22E+02	5.08E+02	5.48E+02
^{85}Kr	3.18E+01	2.68E+01	2.42E+01	1.91E+01	1.94E+01	1.09E+02	1.01E+02
^{3}H		6.95E−02	7.54E−02	9.24E−02	9.37E−02	9.10E−02	8.60E−02
^{232}Th						8.90E+05	8.90E+05
^{231}Pa	1.30E−03						
^{232}U	1.60E−03					8.36E+00	8.33E+00
^{233}U	1.95E−02						2.32E+04
^{234}U	3.07E+02						
^{235}U	2.41E+02	9.43E+03					6.49E+04
^{236}U	1.85E+03	4.01E+03				8.75E+04	
^{238}U	9.34E+05	9.41E+05				6.55E+04	
^{237}Np	6.77E+02	4.56E+02	3.70E+02	2.60E+02		9.73E+03	1.60E+03
^{239}Np						5.80E+01	
^{238}Pu	4.72E+02	1.58E+02	1.35E+03	1.91E+03	2.34E+02	4.89E+03	5.24E+02
^{239}Pu	4.54E+03	6.50E+03	5.30E+03	6.96E+04	7.49E+04	1.66E+02	1.50E+02
^{240}Pu	2.44E+03	2.35E+03	3.50E+03	2.16E+04	2.14E+04	2.93E+02	5.88E+01
^{241}Pu	1.22E+03	1.50E+03	1.35E+03	5.53E+03	2.07E+03	2.94E+02	4.98E+01
^{242}Pu	1.19E+03	4.41E+02				8.42E+01	
^{241}Am	8.60E+01	1.15E+02	1.20E+02	8.73E+02	2.74E+02	1.32E+01	5.02E+00
^{242m}Am						1.54E−01	
^{243}Am	4.85E+02	9.97E+01	4.38E+02	2.10E+02	3.49E+01	9.94E+00	6.86E+00
^{242}Cm		2.79E+00	3.11E+00	2.08E+00	5.70E-01	5.08E−02	5.07E−02
^{243}Cm	9.20E−01	6.18E−01					
^{244}Cm	3.75E+02	2.86E+01	2.63E+02	1.09E+01	1.82E+00	1.38E+01	2.46E+00

Table 2. Waste toxicity indexes.

	Radiotoxicity index	Physical form	Units (e.g.)	Examples (see literature review)
A	Radioactivity hazard	Unspecified	Ci or Bq	51COR, 56PRO, 58PRA, 78COH
B1	Specific activity of nuclide *i* [1]	Nuclide(s) in pure form	Bq per gram or mole of *i*	58PRA
B2	"	Nuclide(s) in fuel rod[2]	Bq per gram or ton[3]	75SVA, 76GUI, 76VER, 77COH,78KBS
B3	"	"	Bq per kWh energy[4]	77COH
B4	"	Nuclide(s) in waste[5]	Bq per WU[9]	71BEL, 72CLA, 76GUI
C1	Relative specific activity	Source and ref. in same form	Bq/m^3 waste÷Bq/m^3 ore	71BEL, 72CLA, 75SVA
D1	Dose risk	External and internal	Sv/y	78KBS, 83KBS
D2	Collective/Committed doses[6]	"	man Sv/Sv (70y, 500y)	31Win, 53NCRP, 76HAU, 77COH, 80COH
D3	Dose-based relative risk (DBRR)	"	Sv/y (source) ÷Sv/y(ref.)	31WIN
D4	DBRR: Number of lethal doses [7]	"	LD_c (Sv) /20 (Sv)	(76VER), 77COH, 78COH, 79INH
D5	DBRR: Relative toxicity	Same as references[8]	Dimensionless	71BEL, 76HAU, 76VER, 87HEC, 95KAN, 95ORN
E1	MPBB (absolute or relative)[9]	"Internal contamination"	Ci or Bq; or dimensionless	53NCRP, 55ICRP, 59ICRP#2, 75SVA
E2	Hazard index (*HI*) based on MPC_w and MPC_a	Dissolved in potable water or dispersed in air	m^3 of water or of air per WU[10]	71BEL,74MCG,75SVA,76GUI,76HAU,76SOU,77COH,82 CRO
E3	Relative *HI*'s	Comparable forms	Dimensionless	Almost all recent publications
E4	Number of ALI's (ingested) [11] or ALI's (inhaled) (abs. or rel.)	Soluble or insoluble form Gaseous and/or aerosol	Bq source / ALI (Bq/man y)	77ICRP#6, 78ADA, 87HEC, 95KAN
E5	Hazard index DWC[12] (ingestion) Hazard index in DAC (inhaled)	Radionucl. contained in water Radionuclide dispersed in air[9]	Bq (or Ci) / m^3	77ICRP#6, 78ADA, 79ICRP#30

[1] The nuclide *i* in the waste has a radioactivity of A_i Bq and the mass m_i, and thus a specific activity of $S_i=A_i/m_i$; the element activity is the sum of the isotope activities; the mass consists of the isotope masses and "contamination" or dilution masses (taken to be m_0) of same element; thus $S_i=A_i/(m_i+m_0)$. Sometimes specific activity refers to the "target mass", W, or "target volume", V (fuel rod, waste glass, ore, etc), in which case one defines the (macroscopic) specific activity $S_i = A_i/W$ or $= A_i/V$. $A_{tot} = \Sigma A_i$.. In the text we abbreviate $\Sigma S_i=Q_0$.

[2] When referring to spent fuel rods, these must be specified: enrichment, chemical form,, power density, burn-up, etc

[3] Of heavy metal, or of oxide, etc.

[4] Heat energy, GWh_{th} or electric energy (in which case the thermodynamic efficiency should be specified) GWh_e.

[5] Specified waste form: liquid storage, solifified (oxide, glass, etc), etc.

[6] Or dose equivalents.

[7] Lethal dose due to radiation may be assumed to be 20 Sv (see text).

[8] Source (waste) and reference hazard of comparable sort, e.g. radium and daughters in uranium ore (natural abundance 3 ppm, typical ore 0.2%, pitchblende 70%) needed to produce the uranium in the fuel elements, or amount of uranium consumed in the nucler reactions, and physical form (e.g. waste nuclide in UO_2 matrix or in glass; uranium in ore).

[9] MPBB = Maximum Permissible Body Burden.

[10] WU=Waste Unit, e.g. per ton spent fuel element, or IHM (Initial Heavy Metal), or GWh_{th} or GWh_e, etc

[11] ALI=Annual Limits of Intake (inhalation or ingestion) of radionuclide in Bq.

[12] DWC= Derived Water Concentration, calculated on basis of ALI values. DAC = Derived Air Concentrations, based on ALI(inhalation)

Table 3. The most extreme changes from ICRP#2+#6 to ICRP#61

Nuclide	$(MPC)_w$ (Bq/m^3)	DWC (Bq/m^3)	$DWC/(MPC)_w$
^{237}Np	1.1×10^{6}	3.7×10^{3}	0.0034
^{227}Ac	7.4×10^{5}	8.7×10^{3}	0.012
^{231}Pa	3.3×10^{5}	8.7×10^{3}	0.026
^{250}Cf	3.7×10^{6}	1.2×10^{5}	0.032
$^{249, 251}Cf$	1.5×10^{6}	5.0×10^{4}	0.033
^{147}Sm	2.2×10^{7}	7.5×10^{5}	0.034
^{115}In	3.3×10^{7}	1.2×10^{6}	0.036
$^{241, 242m, 243}Am$	1.5×10^{6}	6.2×10^{4}	0.041
$^{245, 246, 247}Cm$	1.5×10^{6}	6.2×10^{4}	0.041
^{244}Cm	2.6×10^{6}	1.1×10^{5}	0.042
- - -	- - -	- - -	- - -
^{59}Ni	7.4×10^{7}	1.1×10^{9}	15
^{203}Hg	7.4×10^{6}	1.1×10^{8}	15
^{45}Ca	3.3×10^{6}	7.5×10^{7}	23
^{187}Re	1.1×10^{9}	2.5×10^{10}	23
^{226}Ra	3.7×10^{3}	8.7×10^{4}	24
^{134}I	3.7×10^{7}	1.0×10^{9}	27
^{63}Ni	1.1×10^{7}	3.7×10^{8}	34
^{71}Ge	7.4×10^{8}	2.5×10^{10}	34

Table 4. Differences in MPC_w between ICRP#2+#6 and 10CFR20B (outside the normal $\times 10$).

Nuclide	ICRP $(MPC)_w$ (Bq/m^3)	10CFR20B $(MPC)_w$ (Bq/m^3)	ICRP/10CFR20B
^{238}U	2.2×10^5	1.5×10^6	0.15
^{232}U	3.0×10^5	1.1×10^6	0.27
^{233}U	1.5×10^6	1.1×10^6	1.4
^{234}U	1.5×10^6	1.1×10^6	1.4
^{235}U	1.5×10^6	1.1×10^6	1.4
^{236}U	1.9×10^6	1.1×10^6	1.7
^{226}Ra	3.7×10^3	1.1×10^3	3.4
^{252}Cf	2.6×10^6	7.4×10^5	3.5
^{230}U	7.4×10^5	1.9×10^5	3.9
^{125m}Te	7.4×10^7	1.5×10^7	4.9
- - -	- - -	- - -	10
^{90}Sr	1.5×10^5	1.1×10^4	14
^{89}Sr	3.7×10^6	1.1×10^5	34
^{135}I	7.4×10^6	1.5×10^5	49
^{134}I	3.7×10^7	7.4×10^5	50
^{126}I	7.4×10^5	1.1×10^4	67
^{131}I	7.4×10^5	1.1×10^4	67
^{129}I	1.5×10^5	2.2×10^3	68
^{133}I	2.6×10^6	3.7×10^4	70
^{132}I	2.2×10^7	3.0×10^5	73

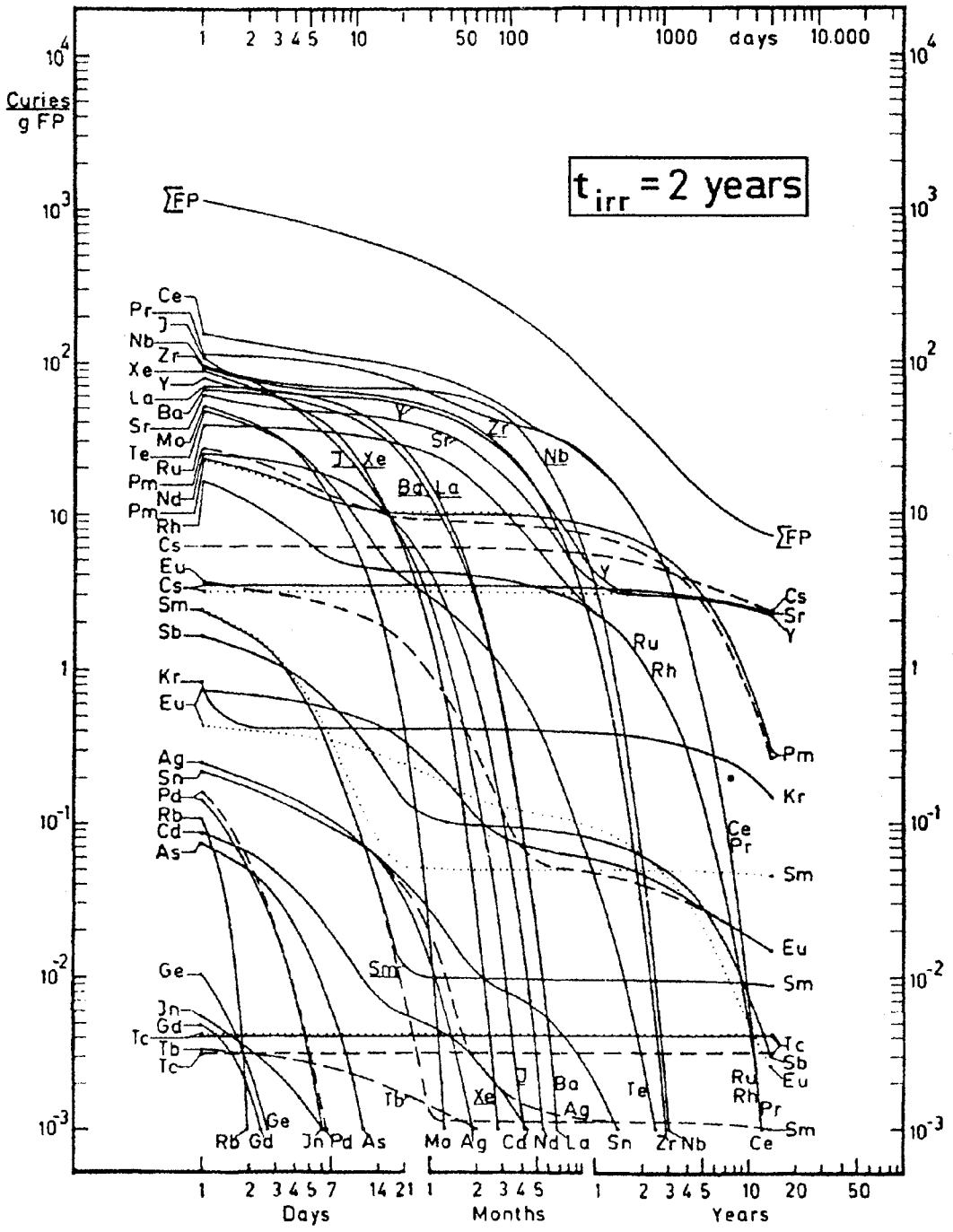

Figure 1. Radioactivity of fission product elements per gram of fission products (58PRA).

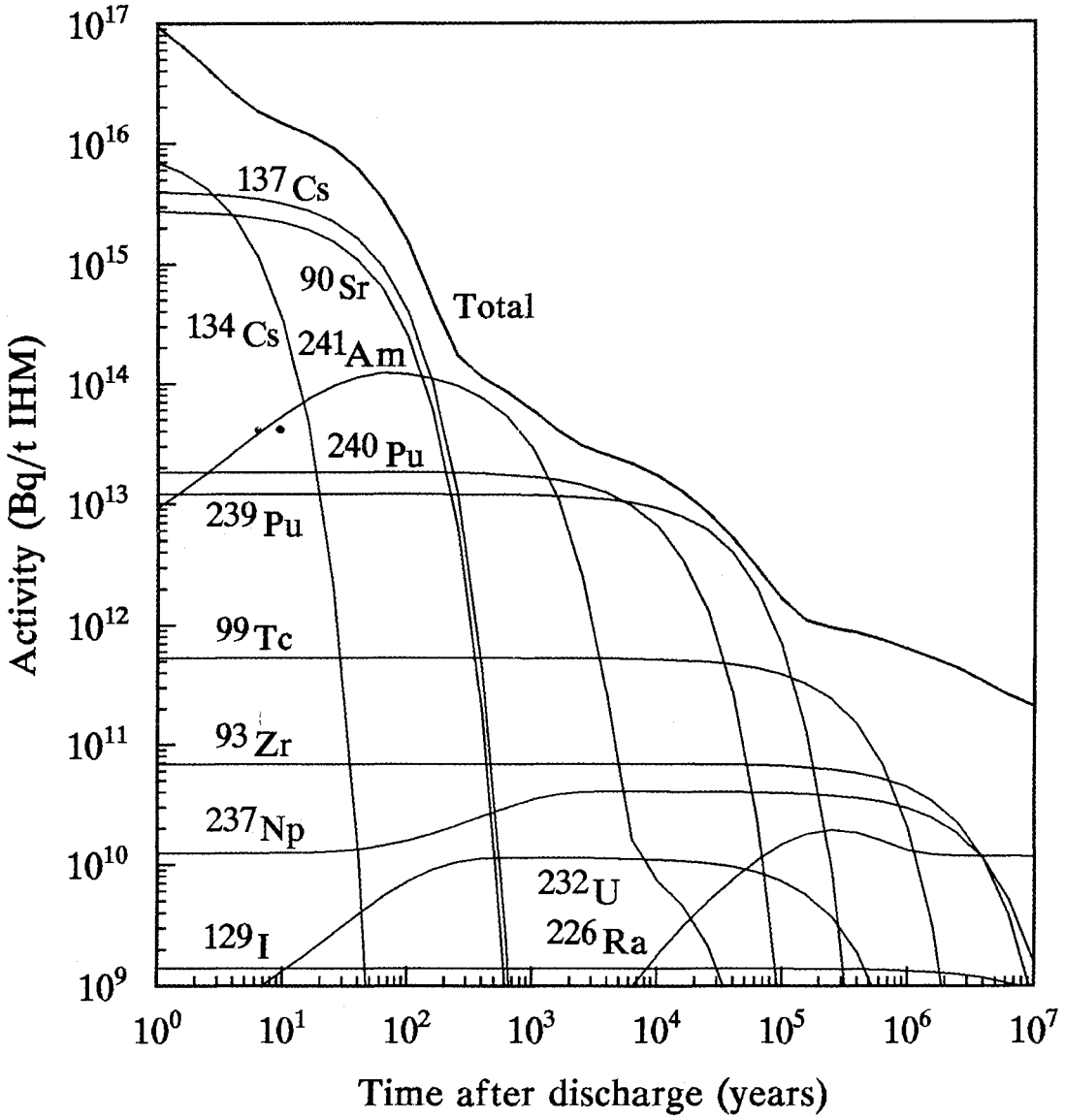

Figure 2. The radioactivity (in Bq) of the radioactive elements in 1 ton spent PWR fuel. Initial enrichment 3.1%, burnup 33 MWd/kg at a power density of 34.4 kW/kg IHM. Calculated from activity data at discharge from reactor obtained by OCR from 77KJE.

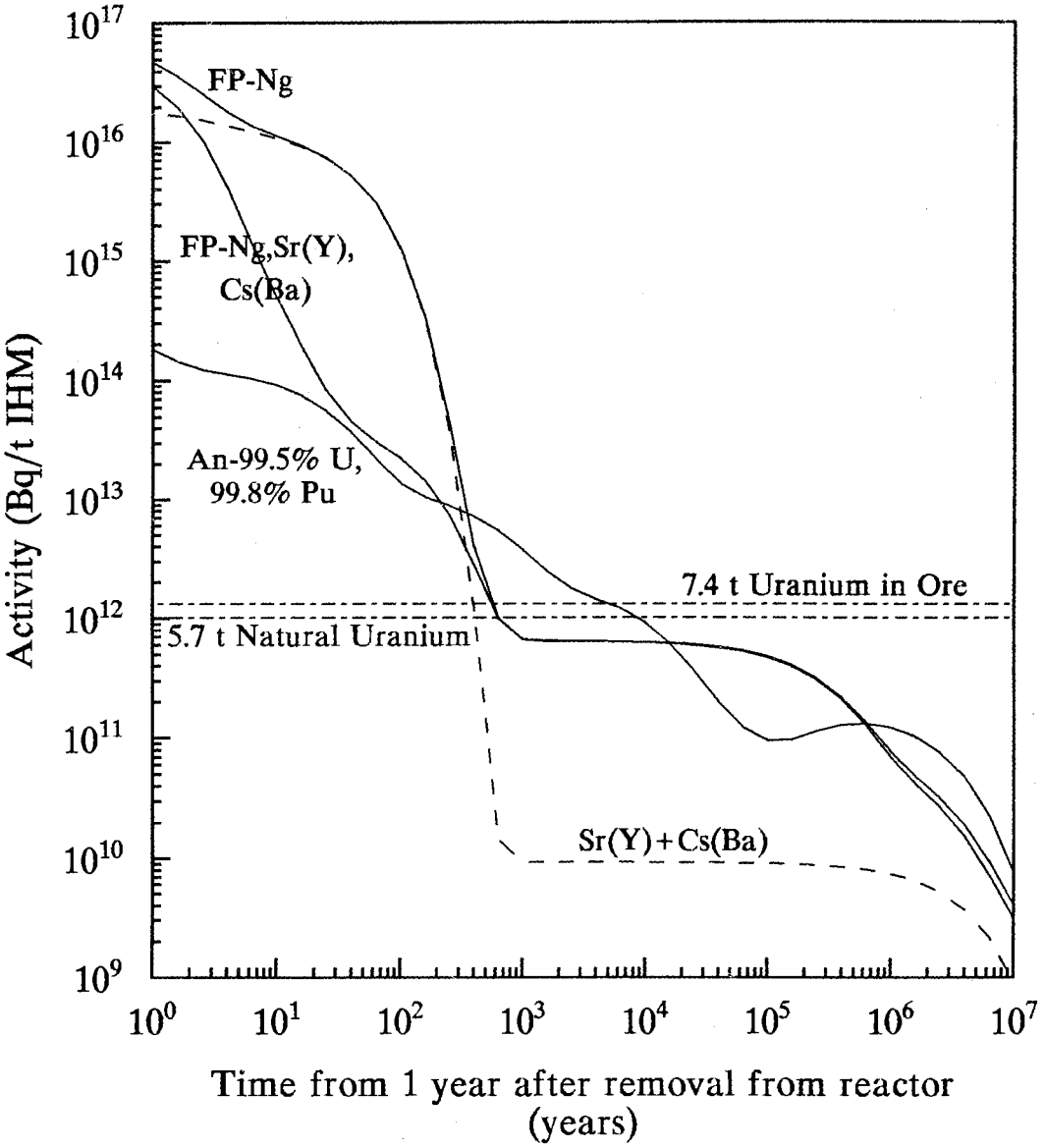

Figure 3. Activity analysis: Comparison between radioactivity in high-level waste per ton reprocessed spent uranium PWR fuel and natural uranium including daughter products. Similar to original Figure in 75SVA, but based on data from 77KJE to facilitate comparisons.

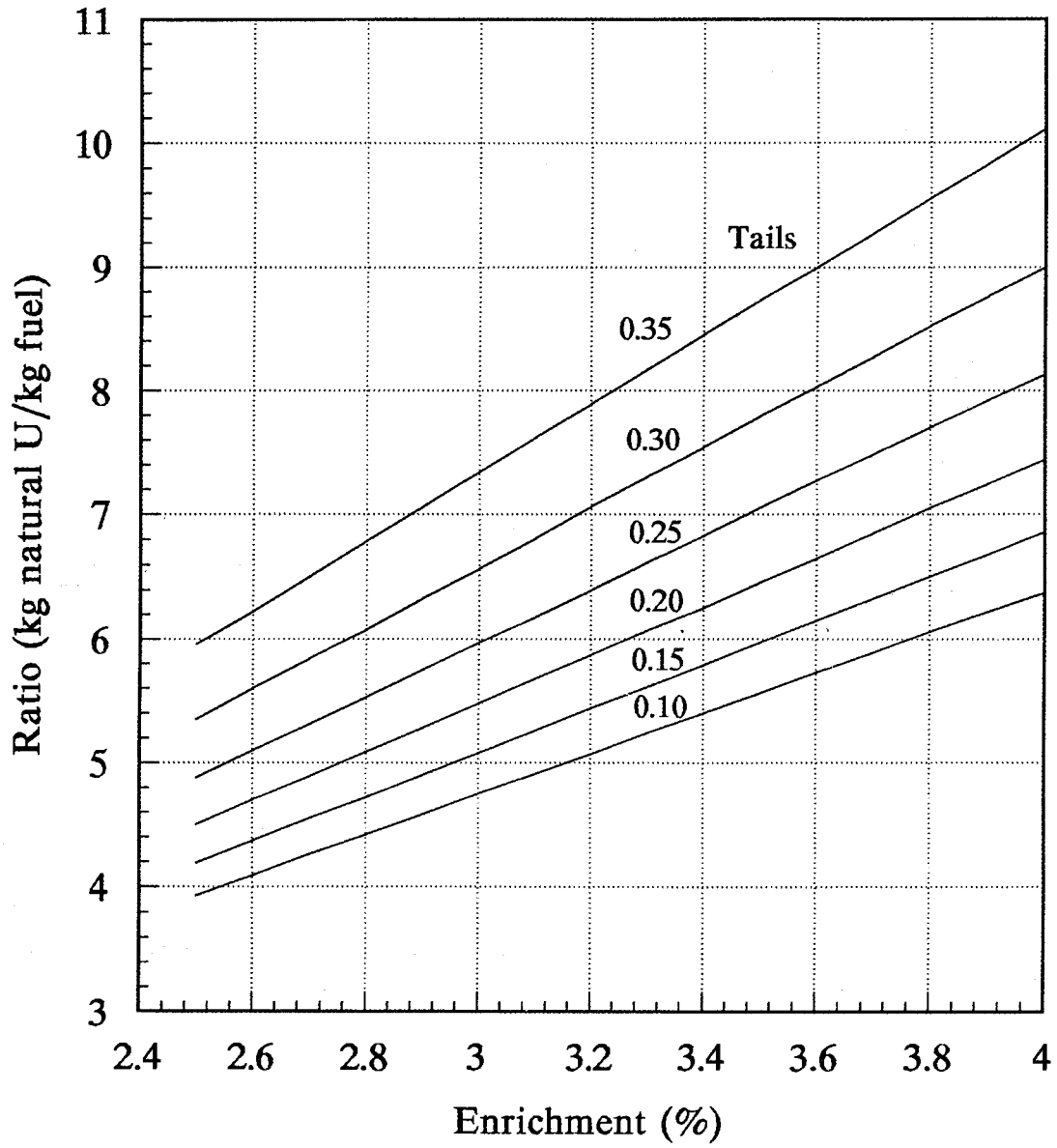

Figure 4. The mass of natural uranium needed to produce one unit mass of enriched uranium as a function of enrichment for some tails compositions. The tails value used in enrichment depends on plant performance, energy costs and costs for feed material (UF_6). Typical values are in the range 0.2% to 0.3%.

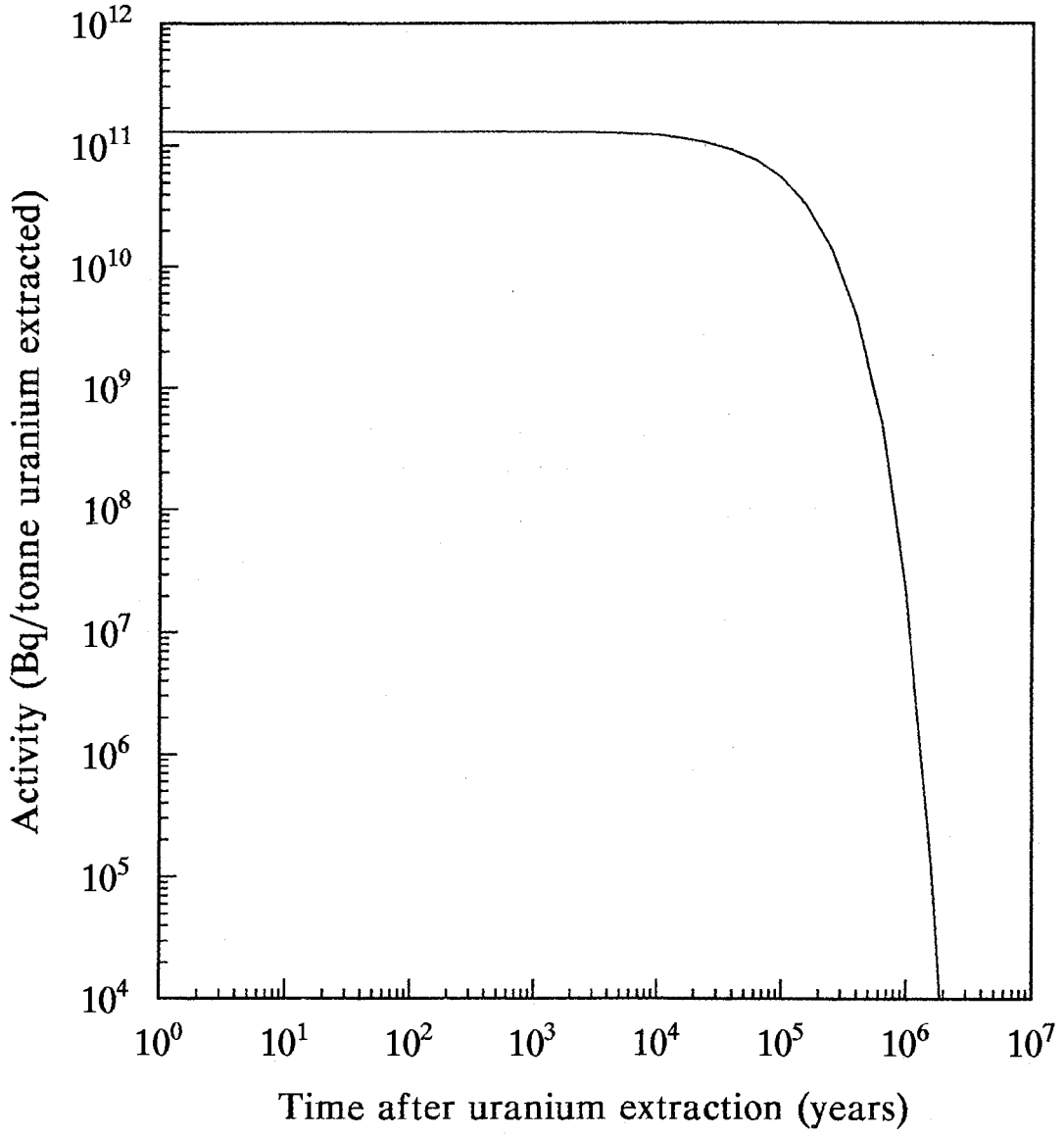

Figure 5. The activity of mine refuse from production of one ton of natural uranium as function of time after uranium extraction.

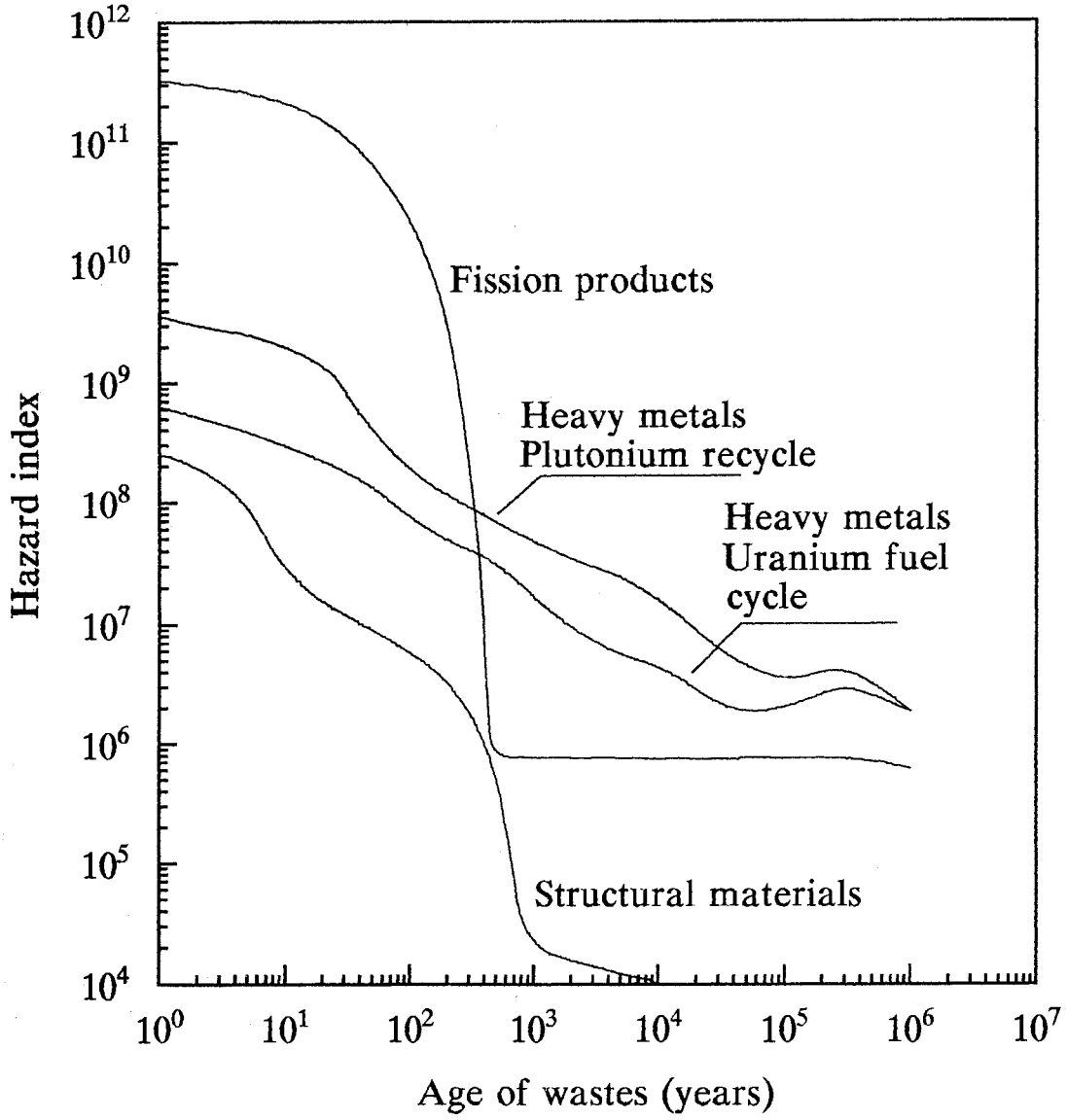

Figure 6. Hazard index (m^3 of water) of radioactive wastes per ton spent PWR fuel (burn-up 34 MWd/kg) for a uranium fuel cycle and a plutonium recycle (replotted from 74MCG). McGrath used hazard index data from the ORIGEN code which are based on 10CRF20B and not on MPC_w according to ICRP. This is not explained anywhere in the original report.

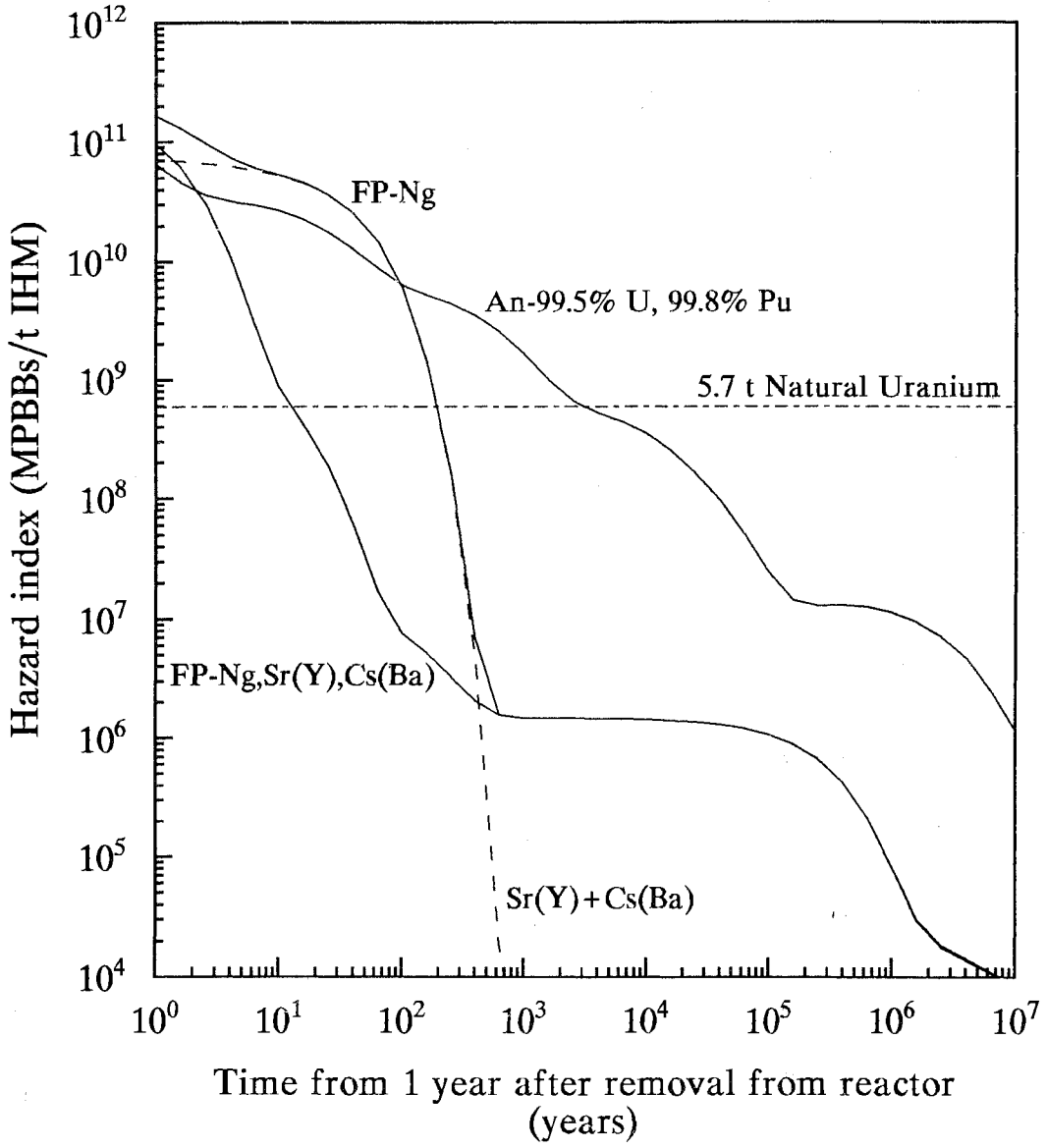

Figure 7. MPBB analysis: Comparison between radioactivity in high level waste per ton reprocessed spent uranium fuel and 5.7 tons natural uranium including daughter products; cf. Fig. 3. Similar to original Figure in 75SVA, but based on data from 77KJE to facilitate comparisons.

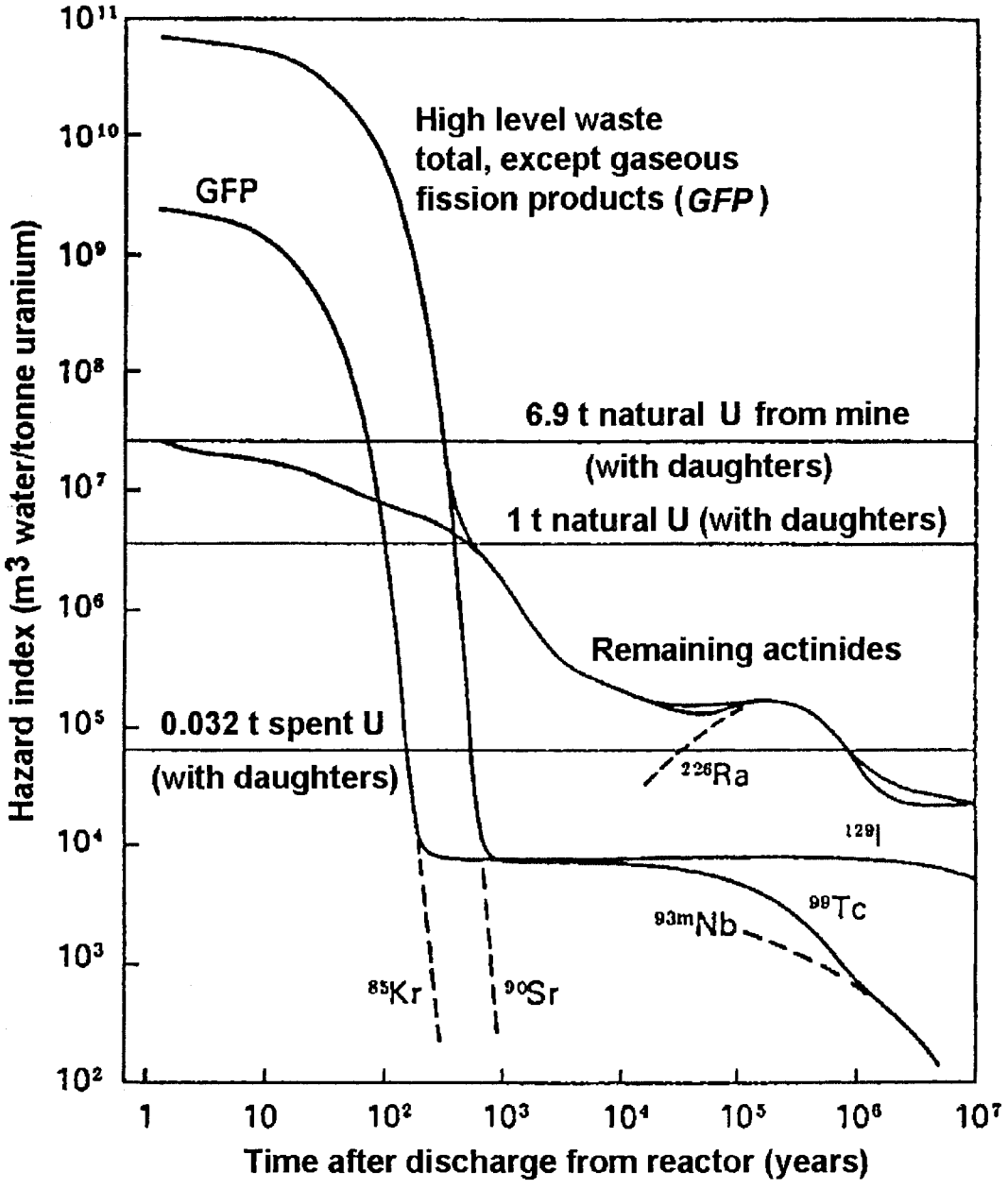

Figure 8. MPC_w analysis: Comparison between radioactivity in high level waste (containing 0.5% U and Pu) per ton reprocessed spent uranium BWR fuel and various amounts of natural uranium including daughter products 76RYD).

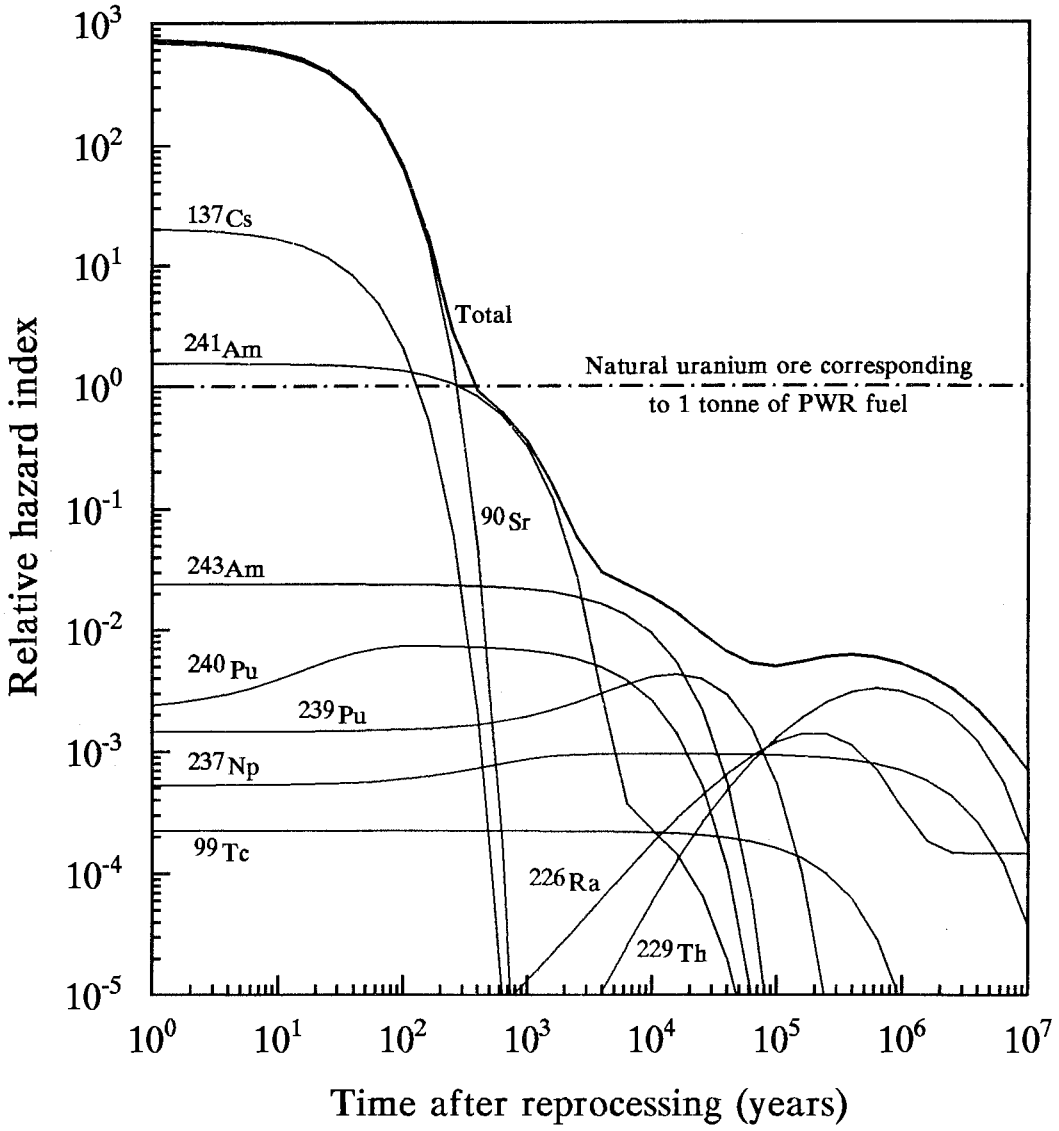

Figure 9. Relative hazard index: HI of high level waste from reprocessing of spent reactor fuel (burn-up 33 MWd/kg IHM, 34.4 kW/kg IHM, enrichment 3.1%) divided by HI of the uranium ore needed to produce the fuel and assuming no production losses (based on fuel data in 77KJE).

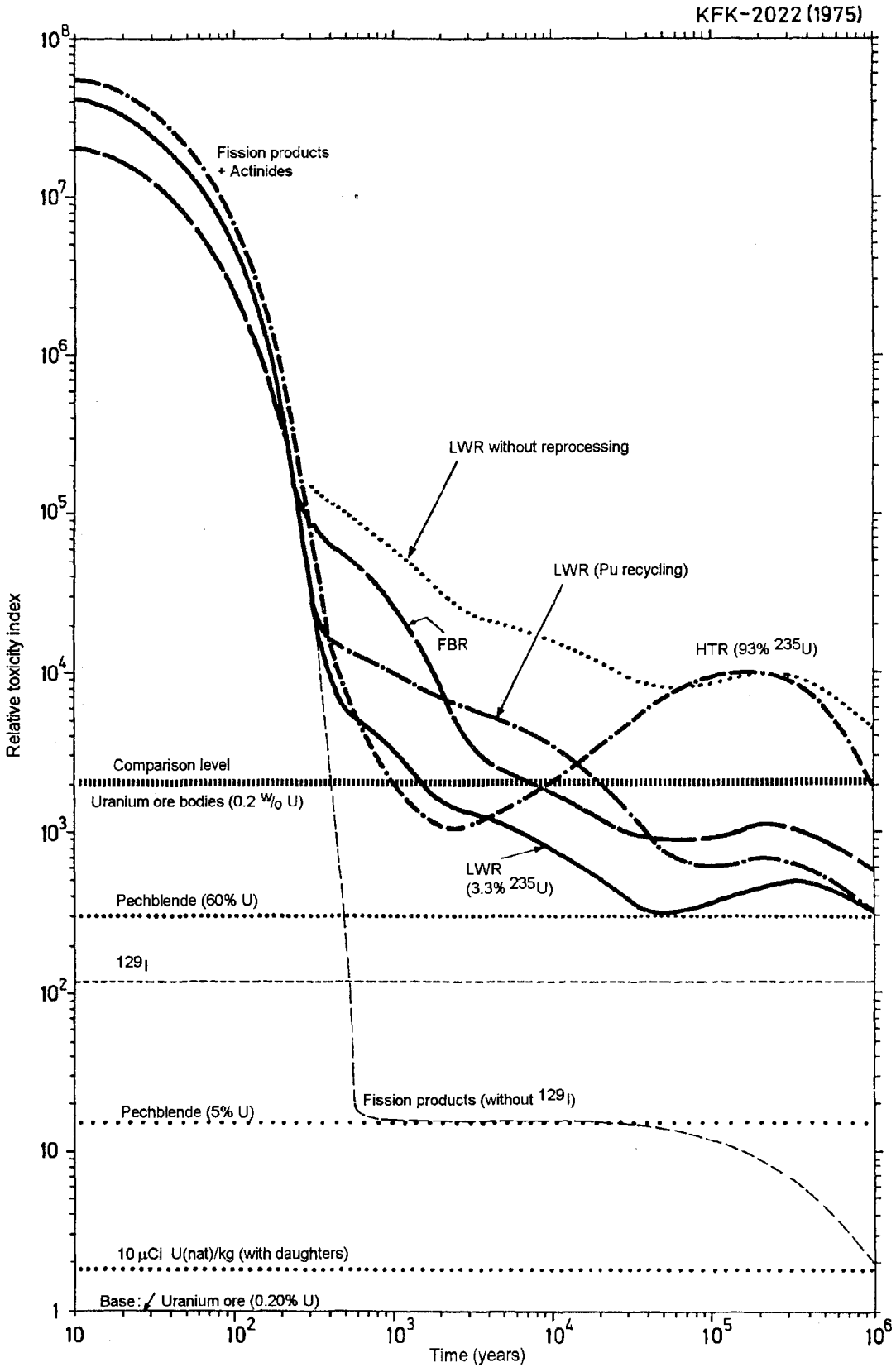

Figure 10. Relative hazard index: As Fig. 6 but for several fuel cycle options and uranium ores (75HAU). The hazard reference is an uranium ore with 0.20% uranium. The comparison level corresponds to the same ore, but with the same volume as the repository.

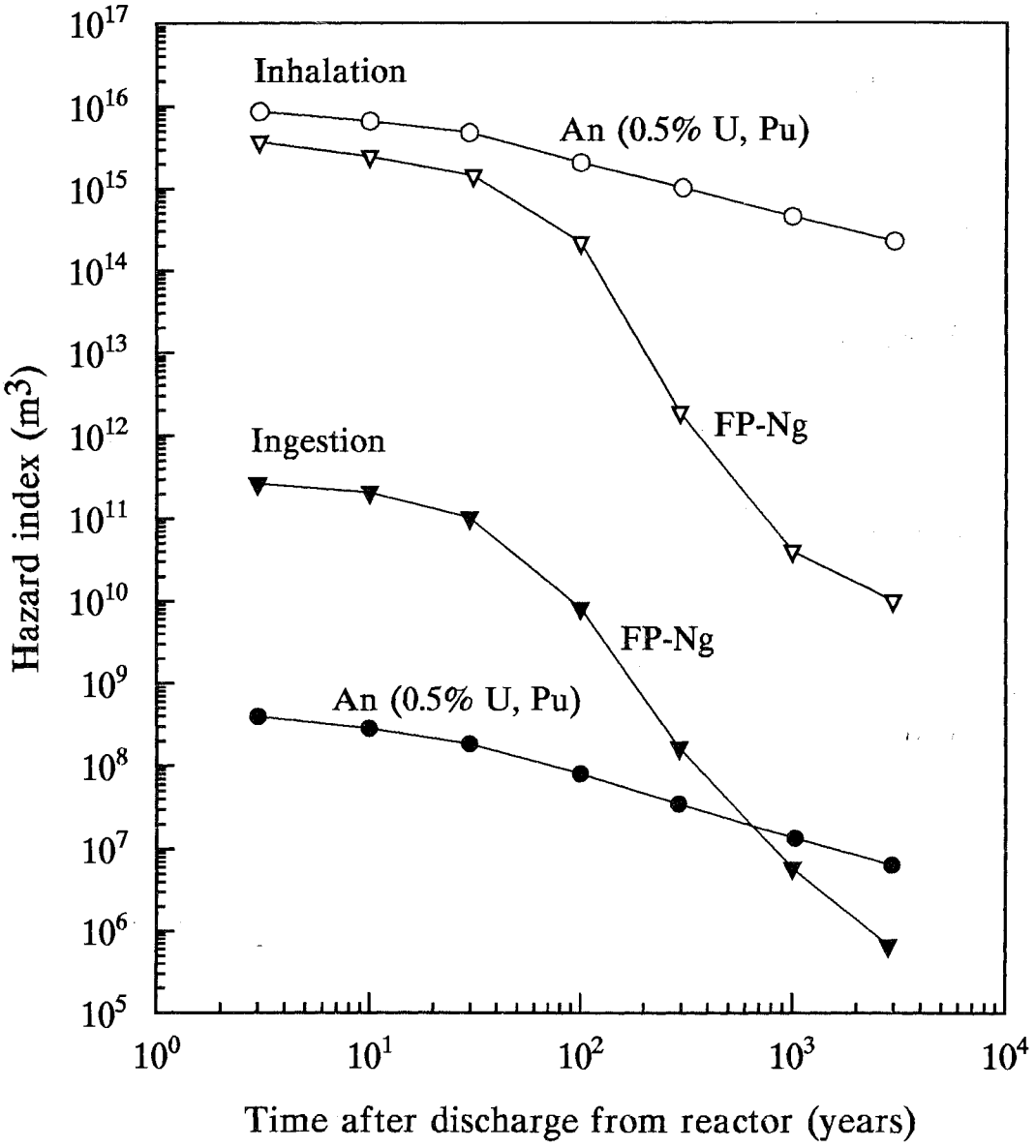

Figure 11. Comparison between inhalation and ingestion hazards (measured in m^3 of MPC_a and MPC_w) (based on 75SVA).

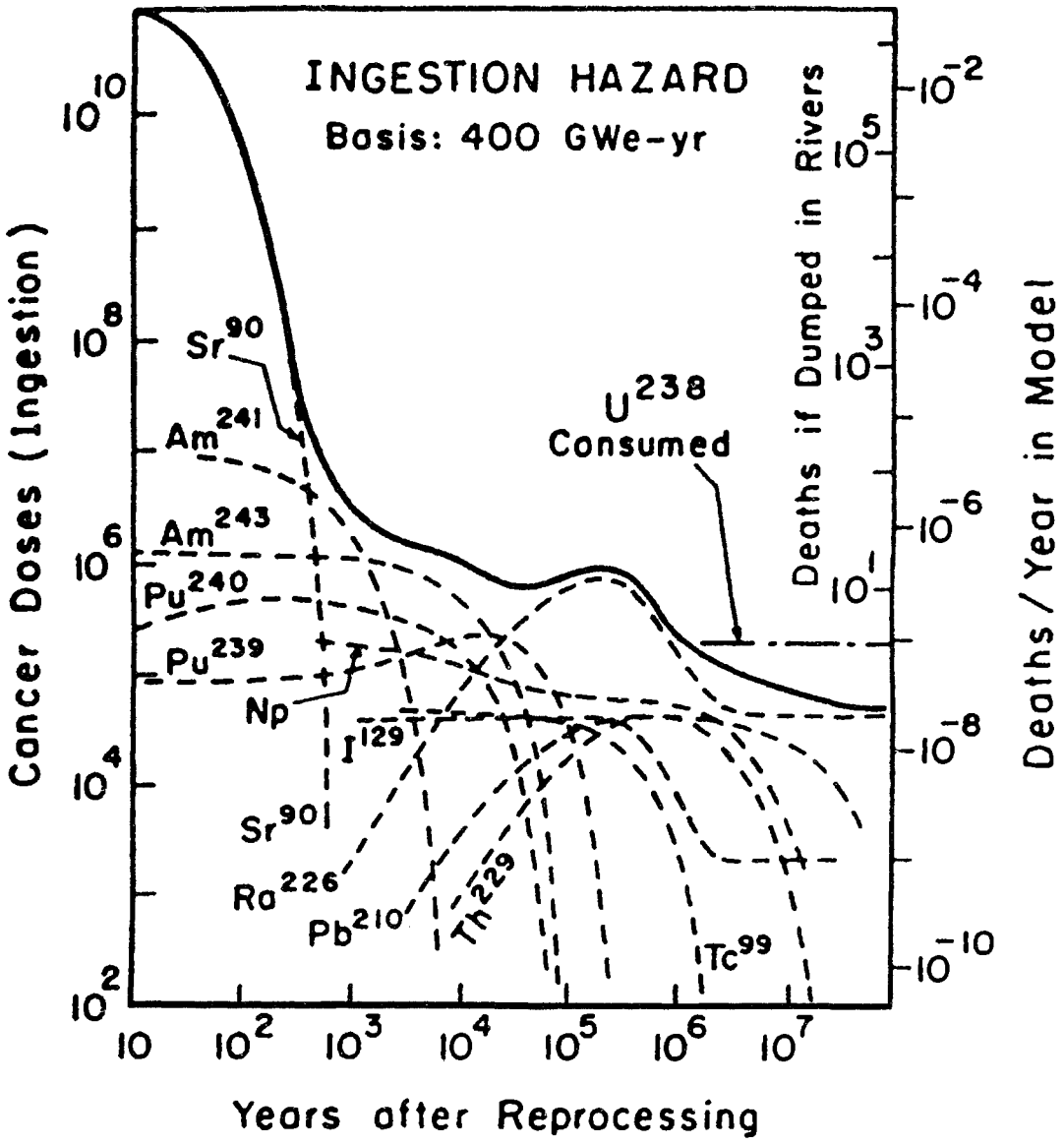

Figure 12. Cancer doses by ingestion of radionuclides from 400 GWy of nuclear electricity if all material were ingested at one time by humans in soluble, digestible form (77COH).

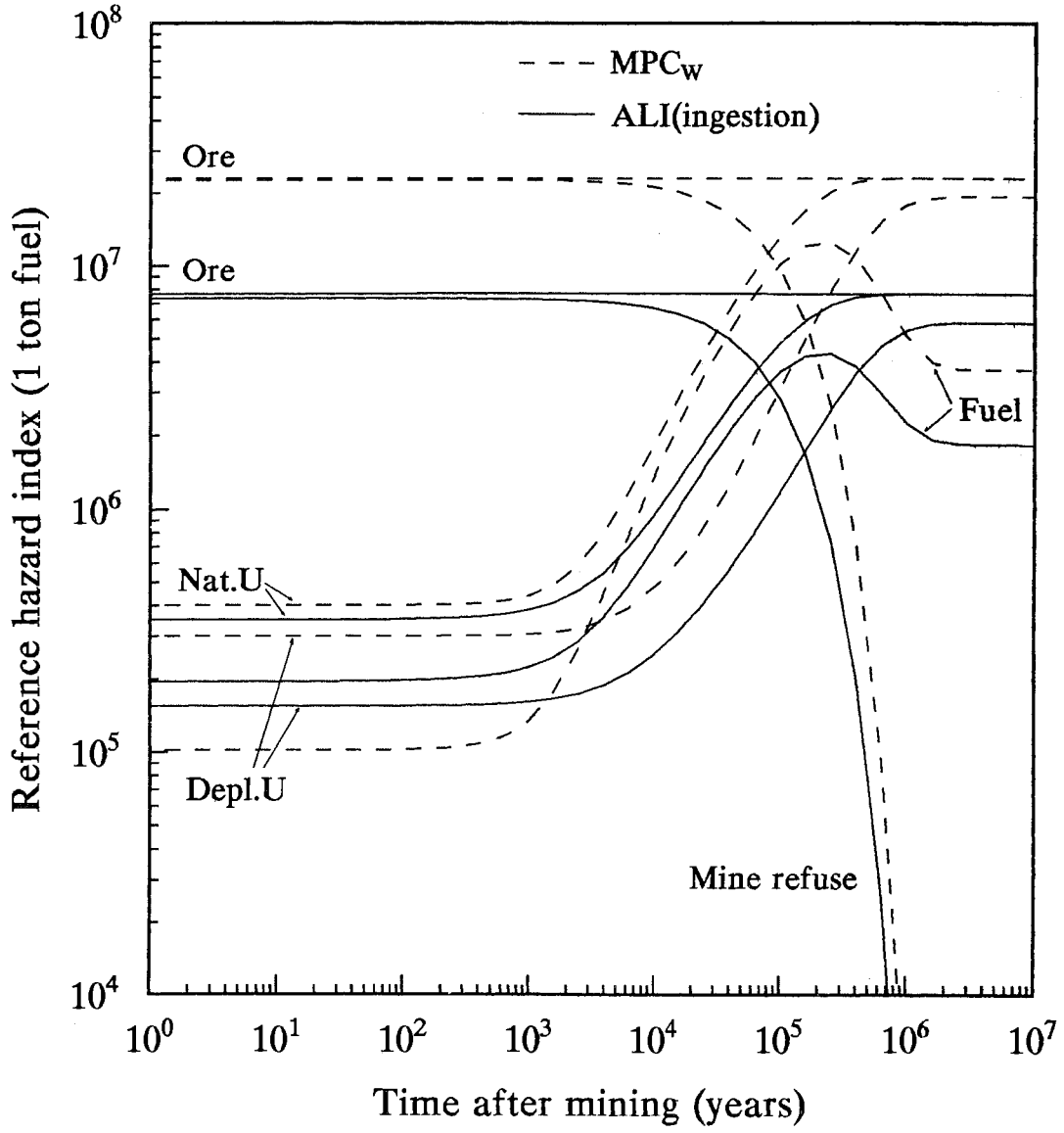

Figure 13. HI_{ref} as function of time for the five basic hazard reference systems (based on 1 ton 3.1% enriched fuel at 0.2% tails). Data based on 10CFR20B were not included in order to make the Figure more readable.

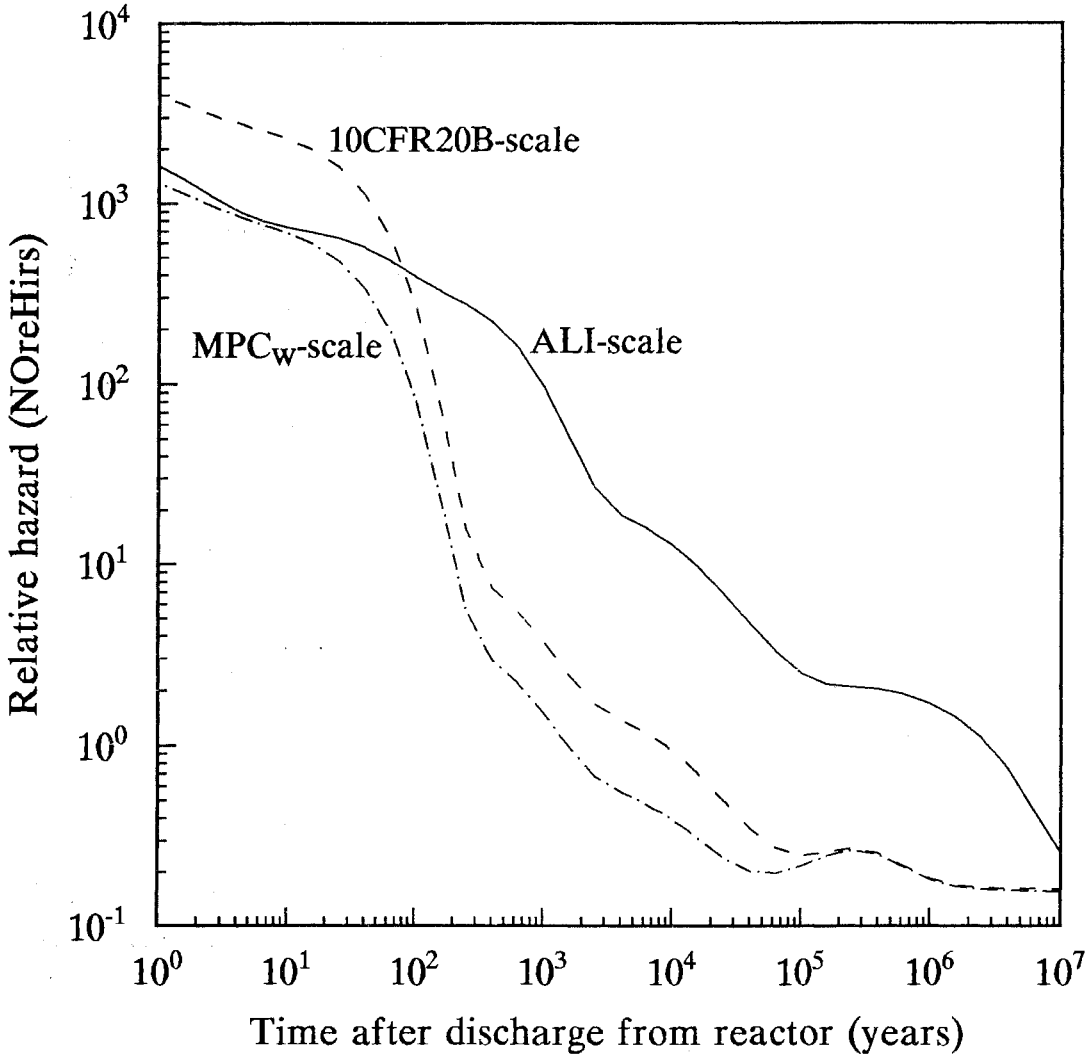

Figure 14. Relative ore-based hazard indices (NOreHirs) for spent PWR fuel (3.1% enrichment, 0.2% tails and a burnup of 33 MWd/t IHM).

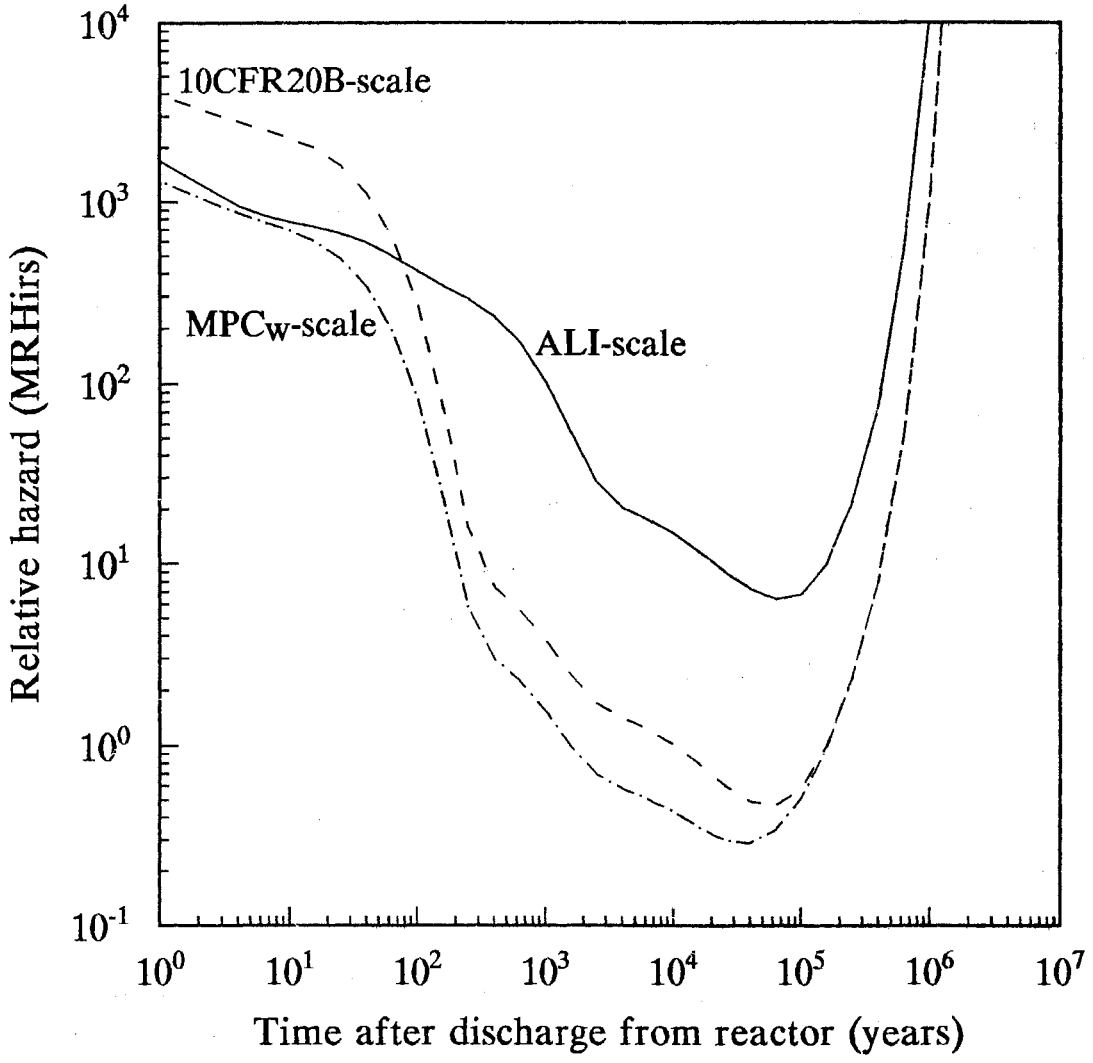

Figure 15. Relative mine refuse based hazard indices (MRHirs) for spent PWR fuel (3.1% enrichment, 0.2% tails and a burnup of 33 MWd/t IHM).

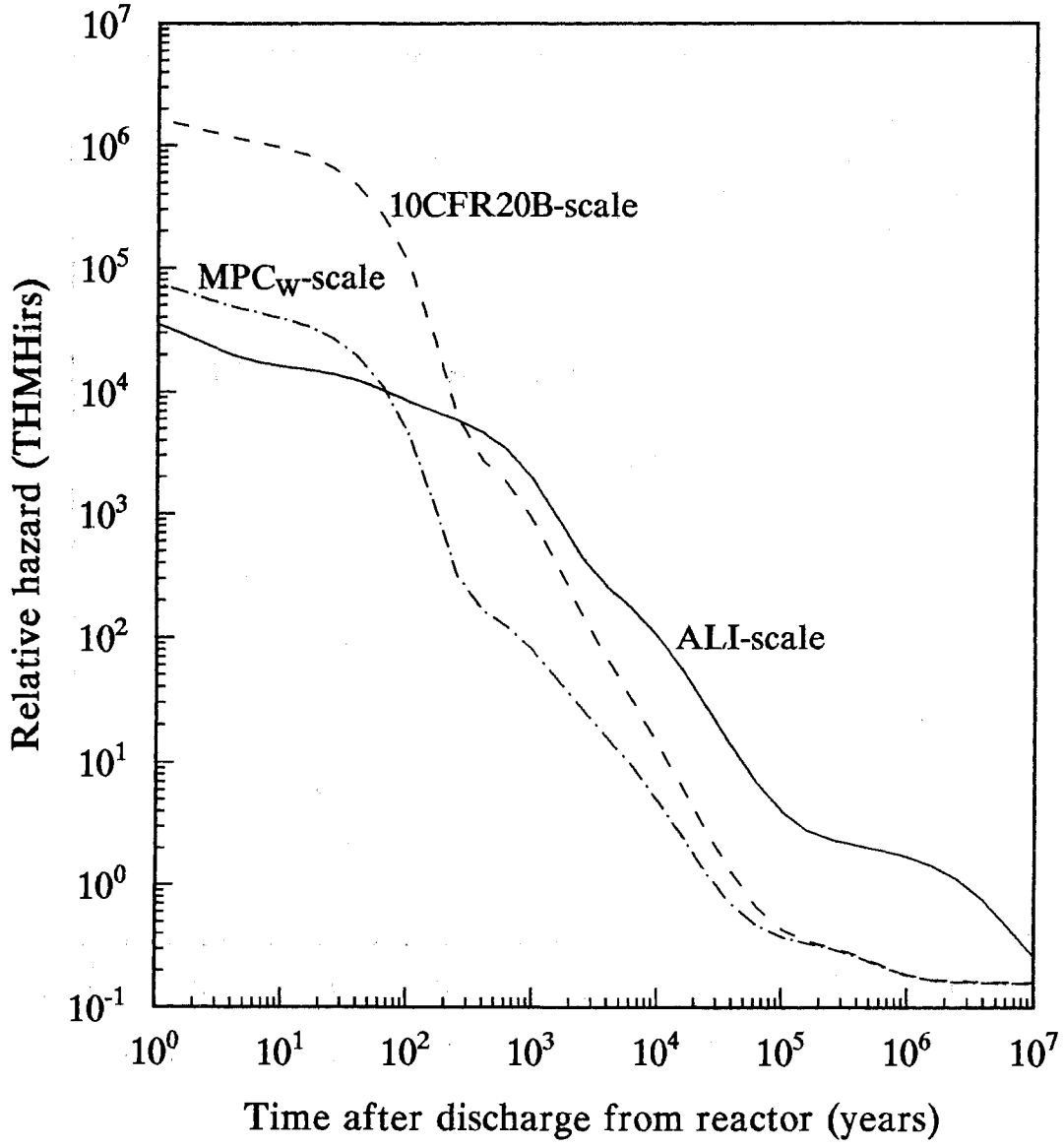

Figure 16. Relative natural uranium based hazard indices (THMHirs) for spent PWR fuel (3.1% enrichment, 0.2% tails and a burnup of 33 MWd/t IHM).

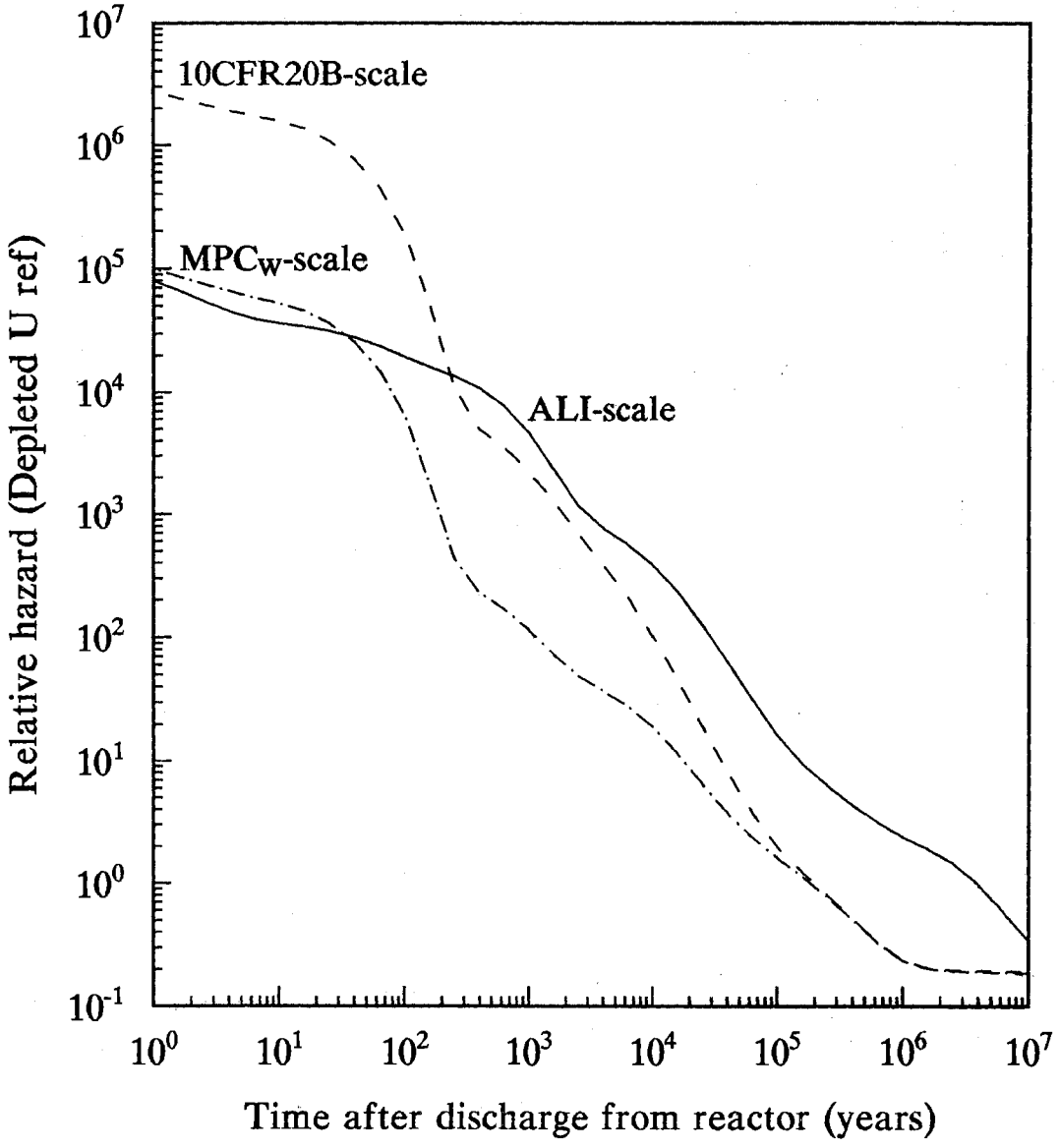

Figure 17. Relative depleted uranium based hazard indices for spent PWR fuel (3.1% enrichment, 0.2% tails and a burnup of 33 MWd/t IHM).

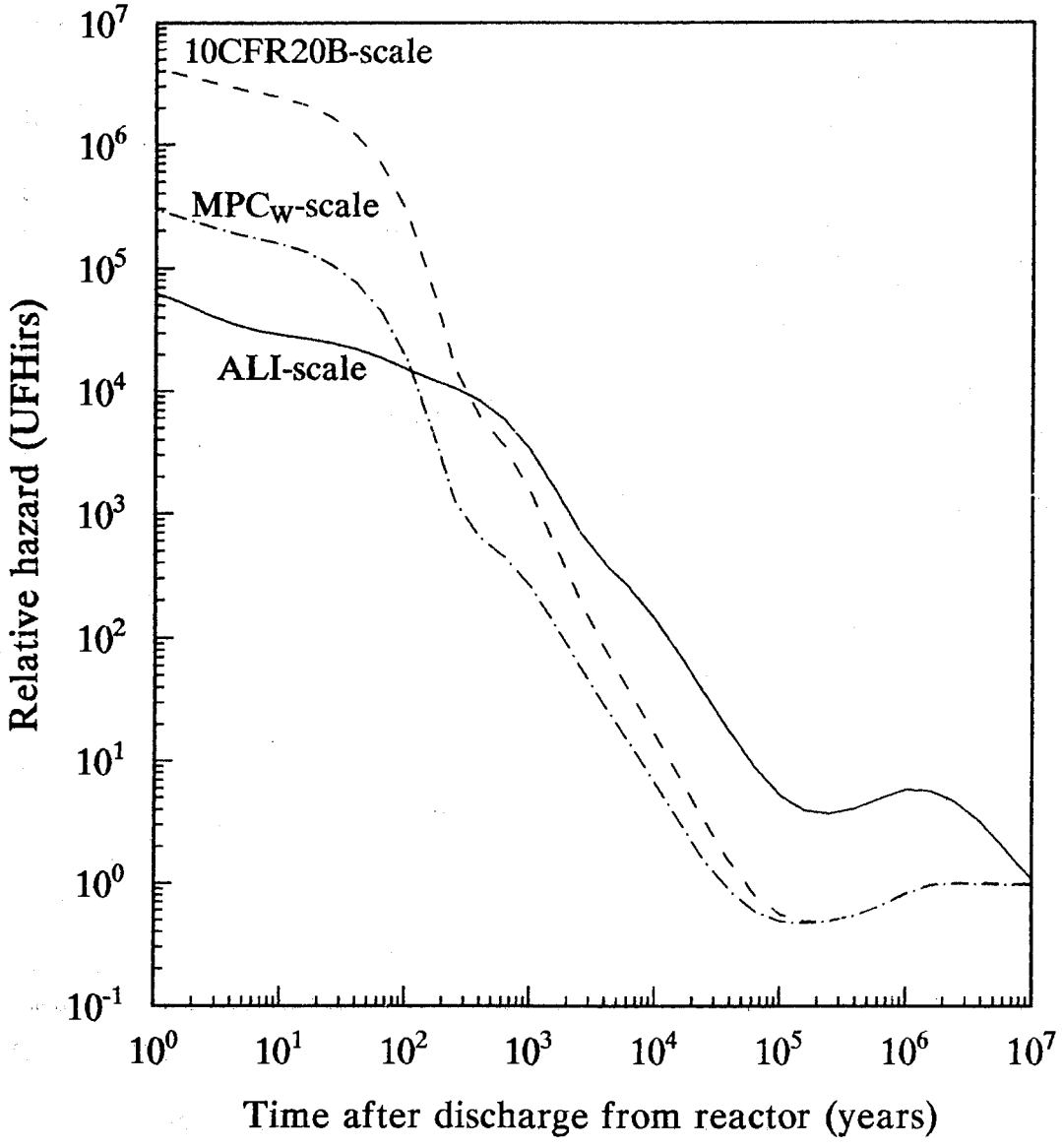

Figure 18. Relative unused fuel based hazard indices for spent PWR fuel (3.1% enrichment, 0.2% tails and a burnup of 33 MWd/t IHM).

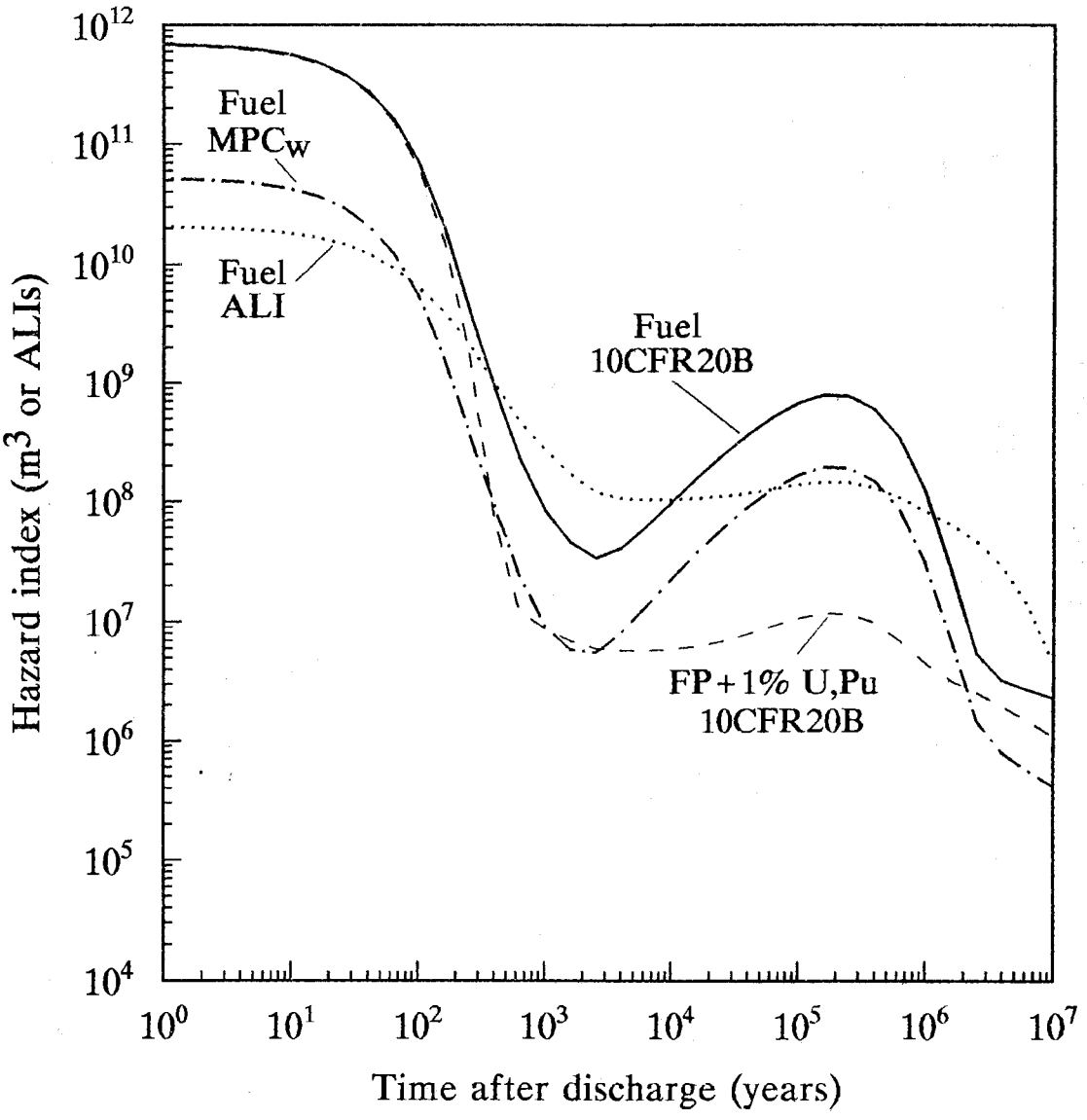

Figure 19. Hazard indices for thermal Th/U breeder fuel and waste at 65 MWd/kg IHM based on 10CFR20B, MPC_w (ICRP 168 h/week) and ALI. Composition data from McGrath (74MCG) were used and extended with selected data from Elowsson (74ELO).

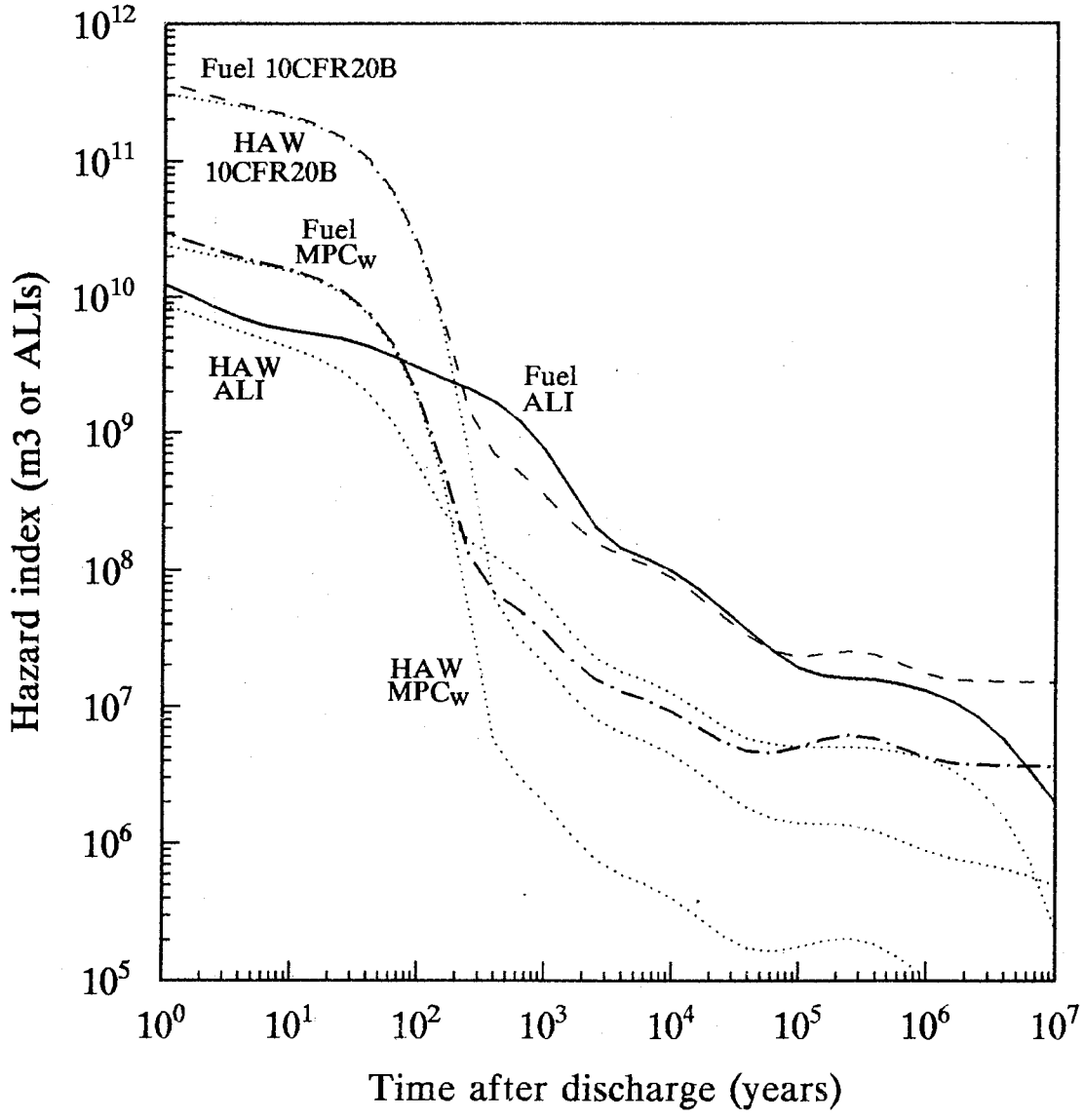

Figure 20. Hazard indices for spent PWR fuel and high level waste (HAW, 0.5% U and 0.2% Pu) as function of time after discharge.

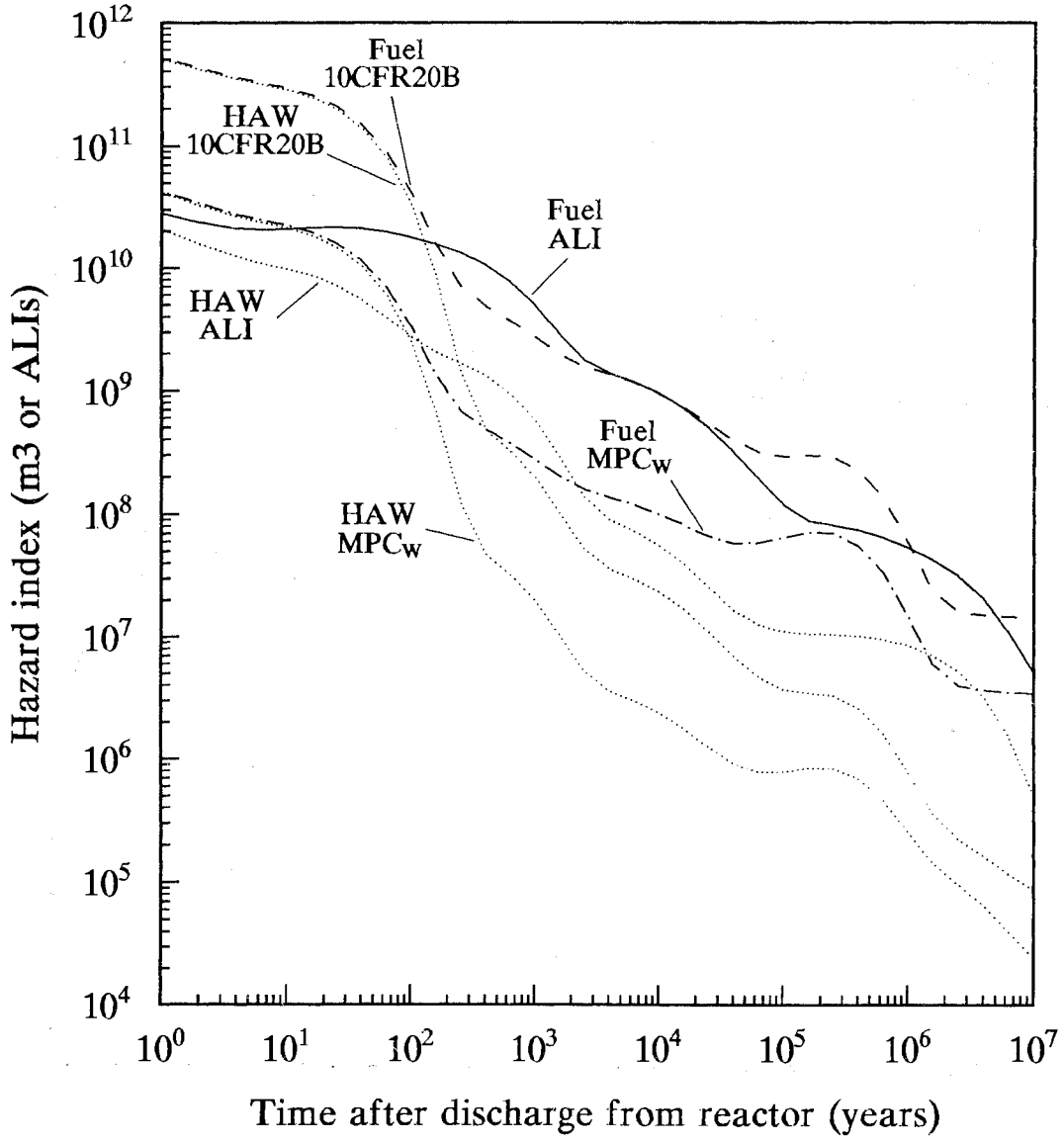

Figure 21. Hazard indices for a LMFBR mix of core and blanket elements and corresponding reprocessing waste (FP, 0.5% U, Pu, 0.1% I) at 45 MWd/t IHM average burnup for the mix. Composition data were taken from Tables in Croff et. al. (82CRO).

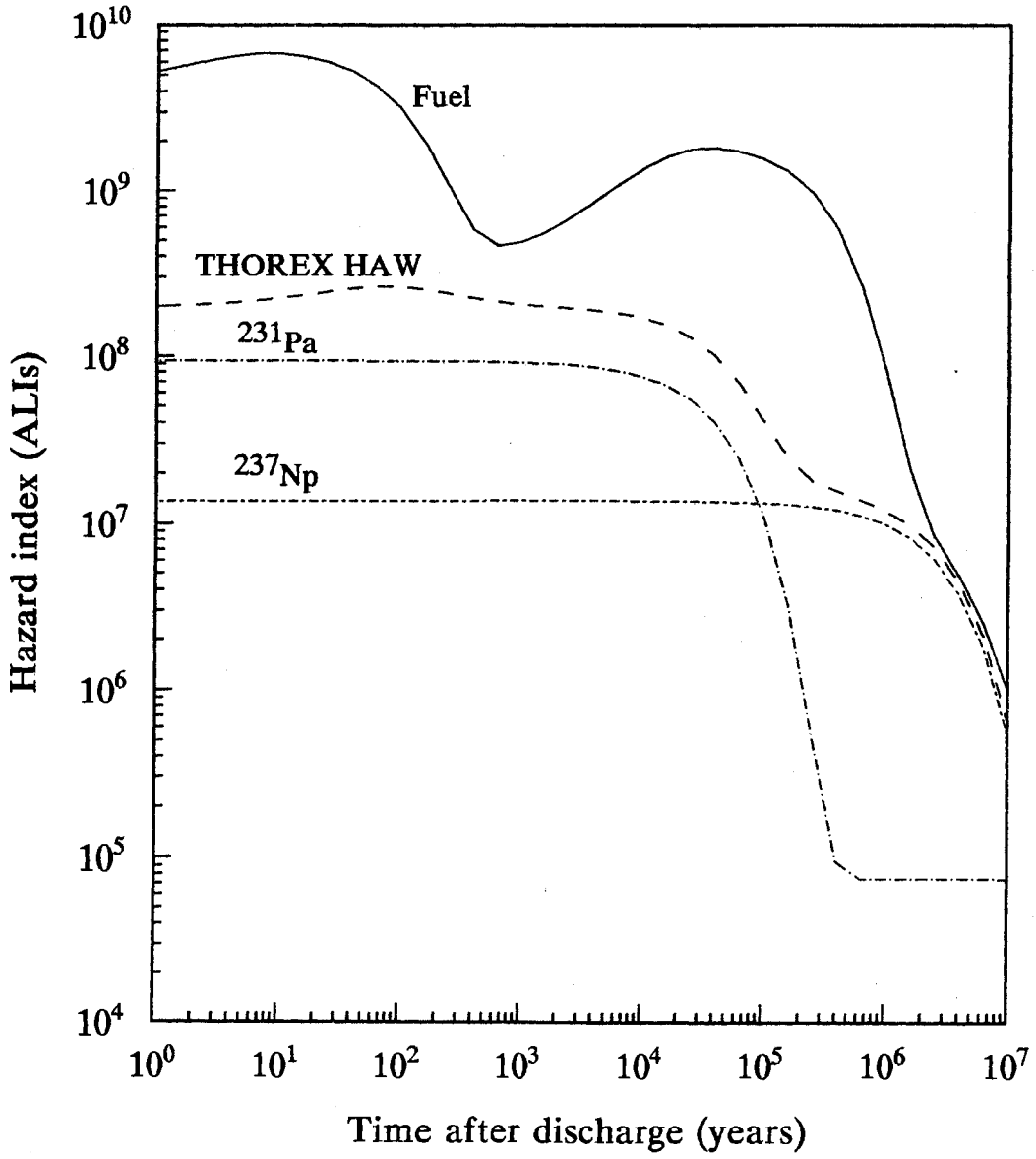

Figure 22. Hazard index for actinides and daughters in spent fuel from a thorium fuelled accelerator driven Energy Amplifier and the resulting high level waste from reprocessing of its spent fuel (in equilibrium cycle, personal communication from J. Magill).

APPENDIX A

Comparison of limits for radionuclide intake

Columns 1-4: mass number (A), isomer, element name, atomic number (Z).

Column 5: MPBB, Maximum Permissible Body Burden in Bq. Recalculated to Bq from μCi in ICRP#2 and ICRP#6 in order to facilitate comparisons.

Column 6: MPC_w, Maximum Permissible Concentration in water (Bq/m^3) for 168 hours per week of occupational exposure (recalculated from $\mu Ci/cm^3$ in ICRP#2 and ICRP#6 in order to facilitate comparisons).

Column 7: MPC_a, Maximum Permissible Concentration in air (Bq/m^3) for use 168 hours per week (recalculated from $\mu Ci/cm^3$ in ICRP#2 and ICRP#6).

Column 8: MPC_w, Maximum Permitted Concentration in water for unrestricted use (Bq/m^3) according to USAEC 1966 as given in 10CFR20B (CFR = US Code of Federal Regulations). Recalculated from μCi/ml to facilitate comparisons. [Note that the 10CFR20B data are typically one order of magnitude lower than the data from ICRP, because 10CFR20B is valid for the general public and ICRP is valid for limiting occupational exposure. However, there are some data with much larger ratios (partly unexplained) than a factor of ten.]

Column 9: MPC_a, Maximum Permitted Concentration in air for unrestricted use (Bq/m^3) according to USAEC 1966 as given in 10CFR20B. Recalculated from μCi/ml to facilitate comparisons.

Column 10: ALI (ingestion) in Bq/man yr (Class f_1 Y) according to ICRP#61 1990.

Column 11: ALI (inhalation) in Bq/man yr (Class f_1 Y) according to ICRP#61 1990.

Column 12: DWC (Derived Water Concentrations) in water (Bq/m^3) for a 168 hr week calculated from ALI (ingestion) according to ICRP#61 1990.

Column 13: DAC (Derived Air Concentrations) in air (Bq/m^3) for a 168 hr week calculated from ALI (inhalation) according to ICRP#61 1990.

1	2	3	4	5	6	7	8	9	10	11	12	13
				ICRP-2&6	ICRP-2&6	ICRP-2&6	10CFR20B	10CFR20B	ICRP	ICRP	ICRP	ICRP
A			Z	MPBB	(MPC)w	(MPC)a	(MPC)w	(MPC)a	ALI oral	ALI inh	DWC	DAC
				(Bq)	(Bq/m3)	(Bq/m3)	(Bq/m3)	(Bq/m3)	(Bq/yr)	(Bq/yr)	(Bq/m3)	(Bq/m3)
3		H	1	3.7E+07	1.1E+09	7.4E+04	1.1E+08	7.4E+03	3.0E+09	3.0E+09	3.7E+09	4.1E+05
7		Be	4	2.2E+07	7.4E+08	7.4E+04	7.4E+07	7.4E+03	2.0E+09	8.0E+08	2.5E+09	1.1E+05
10		Be	4						4.0E+07	6.0E+06	5.0E+07	8.2E+02
11		C	6						2.0E+10	2.0E+10	2.5E+10	2.7E+06
14		C	6	1.1E+07	3.0E+08	3.7E+04	3.0E+07	3.7E+03	9.0E+07	9.0E+07	1.1E+08	1.2E+04
18		F	9	7.4E+05	3.0E+08	7.4E+04	3.0E+07	7.4E+03	2.0E+09	3.0E+09	2.5E+09	4.1E+05
22		Na	11	3.7E+05	1.5E+07	2.2E+03	1.5E+06	2.2E+02	2.0E+07	2.0E+07	2.5E+07	2.7E+03
24		Na	11	2.6E+05	7.4E+07	1.5E+04	7.4E+06	1.5E+03	1.0E+08	2.0E+08	1.2E+08	2.7E+04
28		Mg	12						2.0E+07	6.0E+07	2.5E+07	8.2E+03
26		Al	13						1.0E+07	2.0E+06	1.2E+07	2.7E+02
31		Si	14	3.7E+05	3.3E+08	7.4E+04	3.3E+07	7.4E+03	3.0E+08	9.0E+08	3.7E+08	1.2E+05
32		Si	14						8.0E+07	9.0E+06	1.0E+08	1.2E+03
32		P	15	2.2E+05	7.4E+06	7.4E+02	7.4E+05	7.4E+01	2.0E+07	3.0E+07	2.5E+07	4.1E+03
33		P	15						2.0E+08	3.0E+08	2.5E+08	4.1E+04
35		S	16	3.3E+06	2.2E+07	3.3E+03	2.2E+06	3.3E+02	2.0E+08	6.0E+08	2.5E+08	8.2E+04
36		Cl	17	3.0E+06	3.0E+07	3.7E+03	3.0E+06	3.7E+02	6.0E+07	9.0E+07	7.5E+07	1.2E+04
38		Cl	17	3.3E+05	1.5E+08	3.3E+04	1.5E+07	3.3E+03	6.0E+08	2.0E+09	7.5E+08	2.7E+05
39		Cl	17						8.0E+08	2.0E+09	1.0E+09	2.7E+05
37		Ar	18			3.7E+07		3.7E+06				
41		Ar	18			1.5E+04		1.5E+03				
40		K	19						1.0E+07	1.0E+07	1.2E+07	1.4E+03
42		K	19	3.7E+05	1.1E+08	2.6E+04	1.1E+07	2.6E+03	2.0E+08	2.0E+08	2.5E+08	2.7E+04
43		K	19						2.0E+08	3.0E+08	2.5E+08	4.1E+04
44		K	19						8.0E+08	2.0E+09	1.0E+09	2.7E+05
45		K	19						1.0E+09	4.0E+09	1.2E+09	5.5E+05
41		Ca	20						1.0E+08	1.0E+08	1.2E+08	1.4E+04
45		Ca	20	1.1E+06	3.3E+06	3.7E+02	3.3E+05	3.7E+01	6.0E+07	3.0E+07	7.5E+07	4.1E+03
47		Ca	20	1.9E+05	1.9E+07	2.2E+03	1.9E+06	2.2E+02	3.0E+07	3.0E+07	3.7E+07	4.1E+03
43		Sc	21						3.0E+08	8.0E+08	3.7E+08	1.1E+05
44	m	Sc	21						2.0E+07	3.0E+07	2.5E+07	4.1E+03
44		Sc	21						1.0E+08	4.0E+08	1.2E+08	5.5E+04
46		Sc	21	3.7E+05	1.5E+07	3.0E+03	1.5E+06	3.0E+02	3.0E+07	9.0E+06	3.7E+07	1.2E+03
47		Sc	21	1.9E+06	3.3E+07	7.4E+03	3.3E+06	7.4E+02	8.0E+07	1.0E+08	1.0E+08	1.4E+04
48		Sc	21	3.3E+05	1.1E+07	2.2E+03	1.1E+06	2.2E+02	3.0E+07	5.0E+07	3.7E+07	6.8E+03
49		Sc	21						8.0E+08	2.0E+09	1.0E+09	2.7E+05
44		Ti	22						1.0E+07	4.0E+05	1.2E+07	5.5E+01
45		Ti	22						3.0E+08	9.0E+08	3.7E+08	1.2E+05
47		V	23						1.0E+09	3.0E+09	1.2E+09	4.1E+05
48		V	23	3.0E+05	1.1E+07	2.2E+03	1.1E+06	2.2E+02	2.0E+07	4.0E+07	2.5E+07	5.5E+03
49		V	23						3.0E+09	1.0E+09	3.7E+09	1.4E+05
48		Cr	24						2.0E+08	4.0E+08	2.5E+08	5.5E+04
49		Cr	24						1.0E+09	3.0E+09	1.2E+09	4.1E+05
51		Cr	24	3.0E+07	7.4E+08	1.5E+05	7.4E+07	1.5E+04	1.0E+09	2.0E+09	1.2E+09	2.7E+05
51		Mn	25						7.0E+08	2.0E+09	8.7E+08	2.7E+05
52	m	Mn	25						1.0E+09	3.0E+09	1.2E+09	4.1E+05
52		Mn	25	1.9E+05	1.1E+07	2.6E+03	1.1E+06	2.6E+02	3.0E+07	4.0E+07	3.7E+07	5.5E+03
53		Mn	25						2.0E+09	5.0E+08	2.5E+09	6.8E+04
54		Mn	25	7.4E+05	3.7E+07	3.7E+03	3.7E+06	3.7E+01	7.0E+07	3.0E+07	8.7E+07	4.1E+03
56		Mn	25	7.4E+04	3.7E+07	1.1E+04	3.7E+06	1.1E+03	2.0E+08	6.0E+08	2.5E+08	8.2E+04
52		Fe	26						3.0E+07	1.0E+08	3.7E+07	1.4E+04
55		Fe	26	3.7E+07	3.0E+08	1.1E+04	3.0E+07	1.1E+03	3.0E+08	7.0E+07	3.7E+08	9.6E+03
59		Fe	26	7.4E+05	2.2E+07	1.9E+03	2.2E+06	1.9E+02	3.0E+07	1.0E+07	3.7E+07	1.4E+03
60		Fe	26						1.0E+06	2.0E+05	1.2E+06	2.7E+01
55		Co	27						4.0E+07	1.0E+08	5.0E+07	1.4E+04
56		Co	27						2.0E+07	1.0E+07	2.5E+07	1.4E+03

1	2	3	4	5	6	7	8	9	10	11	12	13
57		Co	27	7.4E+06	1.9E+08	3.7E+04	1.9E+07	3.7E+03	2.0E+08	1.0E+08	2.5E+08	1.4E+04
58	m	Co	27	7.4E+06	1.1E+09	2.2E+05	1.1E+08	2.2E+04	2.0E+09	3.0E+09	2.5E+09	4.1E+05
58		Co	27	1.1E+06	3.7E+07	1.1E+04	3.7E+06	1.1E+03	5.0E+07	4.0E+07	6.2E+07	5.5E+03
60	m	Co	27						4.0E+10	1.0E+11	5.0E+10	1.4E+07
60		Co	27	3.7E+05	1.9E+07	3.7E+03	1.9E+06	3.7E+02	7.0E+06	6.0E+06	8.7E+06	8.2E+02
61		Co	27						7.0E+08	2.0E+09	8.7E+08	2.7E+05
62	m	Co	27						1.0E+09	6.0E+09	1.2E+09	8.2E+05
56		Ni	28						5.0E+07	7.0E+07	6.2E+07	9.6E+03
57		Ni	28						6.0E+07	2.0E+08	7.5E+07	2.7E+04
59		Ni	28	3.7E+07	7.4E+07	7.4E+03	7.4E+06	7.4E+02	9.0E+08	1.0E+08	1.1E+09	1.4E+04
63		Ni	28	7.4E+06	1.1E+07	7.4E+02	1.1E+06	7.4E+01	3.0E+08	6.0E+07	3.7E+08	8.2E+03
65		Ni	28	1.5E+05	3.7E+07	1.1E+04	3.7E+06	1.1E+03	3.0E+08	9.0E+08	3.7E+08	1.2E+05
66		Ni	28						1.0E+07	6.0E+07	1.2E+07	8.2E+03
60		Cu	29						1.0E+09	3.0E+09	1.2E+09	4.1E+05
61		Cu	29						5.0E+08	1.0E+09	6.2E+08	1.4E+05
64		Cu	29	3.7E+05	1.1E+08	2.6E+04	1.1E+07	2.6E+03	4.0E+08	1.0E+09	5.0E+08	1.4E+05
67		Cu	29						2.0E+08	3.0E+08	2.5E+08	4.1E+04
62		Zn	30						5.0E+07	1.0E+08	6.2E+07	1.4E+04
63		Zn	30						9.0E+08	3.0E+09	1.1E+09	4.1E+05
65		Zn	30	2.2E+06	3.7E+07	1.5E+03	3.7E+06	1.5E+02	1.0E+07	1.0E+07	1.2E+07	1.4E+03
69	m	Zn	30	2.6E+04	2.6E+07	3.7E+03	2.6E+06	3.7E+02	2.0E+08	3.0E+08	2.5E+08	4.1E+04
69		Zn	30	3.0E+04	7.4E+08	7.4E+04	7.4E+07	7.4E+03	2.0E+09	5.0E+09	2.5E+09	6.8E+05
71	m	Zn	30						2.0E+08	6.0E+08	2.5E+08	8.2E+04
72		Zn	30						4.0E+07	4.0E+07	5.0E+07	5.5E+03
65		Ga	31						2.0E+09	6.0E+09	2.5E+09	8.2E+05
66		Ga	31						4.0E+07	1.0E+08	5.0E+07	1.4E+04
67		Ga	31						3.0E+08	5.0E+08	3.7E+08	6.8E+04
68		Ga	31						6.0E+08	2.0E+09	7.5E+08	2.7E+05
70		Ga	31						2.0E+09	6.0E+09	2.5E+09	8.2E+05
72		Ga	31	1.9E+05	1.5E+07	3.0E+03	1.5E+06	3.0E+02	4.0E+07	1.0E+08	5.0E+07	1.4E+04
73		Ga	31						2.0E+08	6.0E+08	2.5E+08	8.2E+04
66		Ge	32						1.0E+09	3.0E+09	1.2E+09	4.1E+05
68		Ge	32						2.0E+08	1.0E+08	2.5E+08	1.4E+04
69		Ge	32						5.0E+08	6.0E+08	6.2E+08	8.2E+04
71		Ge	32	3.7E+06	7.4E+08	1.5E+05	7.4E+07	1.5E+04	2.0E+10	2.0E+10	2.5E+10	2.7E+06
75		Ge	32						2.0E+09	3.0E+09	2.5E+09	4.1E+05
77		Ge	32						3.0E+08	4.0E+08	3.7E+08	5.5E+04
78		Ge	32						8.0E+08	8.0E+08	1.0E+09	1.1E+05
69		As	33						1.0E+09	4.0E+09	1.2E+09	5.5E+05
70		As	33						5.0E+08	2.0E+09	6.2E+08	2.7E+05
71		As	33						1.0E+08	2.0E+08	1.2E+08	2.7E+04
72		As	33						3.0E+07	5.0E+07	3.7E+07	6.8E+03
73		As	33	1.1E+07	1.9E+08	2.6E+04	1.9E+07	2.6E+03	3.0E+08	6.0E+07	3.7E+08	8.2E+03
74		As	33	1.5E+06	1.9E+07	3.7E+03	1.9E+06	3.7E+02	6.0E+07	3.0E+07	7.5E+07	4.1E+03
76		As	33	7.4E+05	7.4E+06	1.5E+03	7.4E+05	1.5E+02	4.0E+07	5.0E+07	5.0E+07	6.8E+03
77		As	33	3.0E+06	3.0E+07	7.4E+03	3.0E+06	7.4E+02	2.0E+08	2.0E+08	2.5E+08	2.7E+04
78		As	33						3.0E+08	8.0E+08	3.7E+08	1.1E+05
70		Se	34						4.0E+08	1.0E+09	5.0E+08	1.4E+05
73	m	Se	34						1.0E+09	6.0E+09	1.2E+09	8.2E+05
73		Se	34						1.0E+08	5.0E+08	1.2E+08	6.8E+04
75		Se	34	3.3E+06	1.1E+08	1.5E+04	1.1E+07	1.5E+03	2.0E+07	3.0E+07	2.5E+07	4.1E+03
79		Se	34						2.0E+07	3.0E+07	2.5E+07	4.1E+03
81	m	Se	34						9.0E+08	3.0E+09	1.1E+09	4.1E+05
81		Se	34						2.0E+09	8.0E+09	2.5E+09	1.1E+06
83		Se	34						1.0E+09	4.0E+09	1.2E+09	5.5E+05
74	m	Br	35						5.0E+08	1.0E+09	6.2E+08	1.4E+05
74		Br	35						8.0E+08	3.0E+09	1.0E+09	4.1E+05
75		Br	35						1.0E+09	2.0E+09	1.2E+09	2.7E+05
76		Br	35						1.0E+08	2.0E+08	1.2E+08	2.7E+04

1	2	3	4	5	6	7	8	9	10	11	12	13
77		Br	35						6.0E+08	9.0E+08	7.5E+08	1.2E+05
80	m	Br	35						8.0E+08	6.0E+08	1.0E+09	8.2E+04
80		Br	35						2.0E+09	7.0E+09	2.5E+09	9.6E+05
82		Br	35	3.7E+05	1.1E+08	1.5E+04	1.1E+07	1.5E+03	1.0E+08	2.0E+08	1.2E+08	2.7E+04
83		Br	35						2.0E+09	2.0E+09	2.5E+09	2.7E+05
84		Br	35						7.0E+08	2.0E+09	8.7E+08	2.7E+05
85	m	Kr	36			3.7E+04		3.7E+03				
85		Kr	36			1.1E+05		1.1E+04				
87		Kr	36			7.4E+03		7.4E+02				
88		Kr	36					7.4E+02				
79		Rb	37						1.0E+09	4.0E+09	1.2E+09	5.5E+05
81	m	Rb	37						9.0E+09	1.0E+10	1.1E+10	1.4E+06
81		Rb	37						1.0E+09	2.0E+09	1.2E+09	2.7E+05
82	m	Rb	37						4.0E+08	7.0E+08	5.0E+08	9.6E+04
83		Rb	37						2.0E+07	4.0E+07	2.5E+07	5.5E+03
84		Rb	37						2.0E+07	3.0E+07	2.5E+07	4.1E+03
86		Rb	37	1.1E+06	2.6E+07	3.7E+03	2.6E+06	3.7E+02	2.0E+07	3.0E+07	2.5E+07	4.1E+03
87		Rb	37	7.4E+06	3.7E+07	7.4E+03	3.7E+06	7.4E+02	4.0E+07	6.0E+07	5.0E+07	8.2E+03
88		Rb	37						7.0E+08	2.0E+09	8.7E+08	2.7E+05
89		Rb	37						1.0E+09	5.0E+09	1.2E+09	6.8E+05
80		Sr	38						2.0E+08	4.0E+08	2.5E+08	5.5E+04
81		Sr	38						9.0E+08	3.0E+09	1.1E+09	4.1E+05
83		Sr	38						8.0E+07	3.0E+08	1.0E+08	4.1E+04
85	m	Sr	38	1.9E+06	2.6E+09	3.7E+05	2.6E+08	3.7E+04	8.0E+09	2.0E+10	1.0E+10	2.7E+06
85		Sr	38	2.2E+06	3.7E+07	3.0E+03	3.7E+06	3.0E+02	9.0E+07	1.0E+08	1.1E+08	1.4E+04
87	m	Sr	38						1.0E+09	5.0E+09	1.2E+09	6.8E+05
89		Sr	38	1.5E+05	3.7E+06	3.7E+02	1.1E+05	1.1E+01	2.0E+07	3.0E+07	2.5E+07	4.1E+03
90		Sr	38	7.4E+04	1.5E+05	1.5E+01	1.1E+04	1.1E+00	1.0E+06	7.0E+05	1.2E+06	9.6E+01
91		Sr	38	1.1E+05	2.6E+07	7.4E+03	2.6E+06	7.4E+02	6.0E+07	2.0E+08	7.5E+07	2.7E+04
92		Sr	38	7.4E+04	2.6E+07	7.4E+03	2.6E+06	7.4E+02	1.0E+08	3.0E+08	1.2E+08	4.1E+04
86	m	Y	39						8.0E+08	2.0E+09	1.0E+09	2.7E+05
86		Y	39						5.0E+07	1.0E+08	6.2E+07	1.4E+04
87		Y	39						8.0E+07	1.0E+08	1.0E+08	1.4E+04
88		Y	39						4.0E+07	9.0E+06	5.0E+07	1.2E+03
90	m	Y	39						3.0E+08	5.0E+08	3.7E+08	6.8E+04
90		Y	39	1.1E+05	7.4E+06	1.5E+03	7.4E+05	1.5E+02	2.0E+07	3.0E+07	2.5E+07	4.1E+03
91	m	Y	39	1.9E+05	1.1E+09	3.0E+05	1.1E+08	3.0E+04	5.0E+09	9.0E+09	6.2E+09	1.2E+06
91		Y	39	1.9E+05	1.1E+07	3.7E+02	1.1E+06	3.7E+01	2.0E+07	6.0E+06	2.5E+07	8.2E+02
92		Y	39	7.4E+04	2.2E+07	3.7E+03	2.2E+06	3.7E+02	1.0E+08	3.0E+08	1.2E+08	4.1E+04
93		Y	39	7.4E+04	1.1E+07	2.2E+03	1.1E+06	2.2E+02	4.0E+07	1.0E+08	5.0E+07	1.4E+04
94		Y	39						8.0E+08	3.0E+09	1.0E+09	4.1E+05
95		Y	39						1.0E+09	6.0E+09	1.2E+09	8.2E+05
86		Zr	40						5.0E+07	1.0E+08	6.2E+07	1.4E+04
88		Zr	40						1.0E+08	8.0E+06	1.2E+08	1.1E+03
89		Zr	40						6.0E+07	1.0E+08	7.5E+07	1.4E+04
93		Zr	40	3.7E+06	3.0E+08	1.5E+03	3.0E+07	1.5E+02	5.0E+07	2.0E+05	6.2E+07	2.7E+01
95		Zr	40	7.4E+05	2.2E+07	1.5E+03	2.2E+06	1.5E+02	5.0E+07	5.0E+06	6.2E+07	6.8E+02
97		Zr	40	1.9E+05	7.4E+06	1.5E+03	7.4E+05	1.5E+02	2.0E+07	7.0E+07	2.5E+07	9.6E+03
88		Nb	41						2.0E+09	8.0E+09	2.5E+09	1.1E+06
89	a	Nb	41						4.0E+08	2.0E+09	5.0E+08	2.7E+05
89	b	Nb	41						2.0E+08	7.0E+08	2.5E+08	9.6E+04
90		Nb	41						4.0E+07	1.0E+08	5.0E+07	1.4E+04
93	m	Nb	41	7.4E+06	1.5E+08	1.5E+03	1.5E+07	1.5E+02	3.0E+08	7.0E+07	3.7E+08	9.6E+03
94		Nb	41						4.0E+07	7.0E+06	5.0E+07	9.6E+02
95	m	Nb	41						8.0E+07	1.0E+08	1.0E+08	1.4E+04
95		Nb	41	1.5E+06	3.7E+07	7.4E+03	3.7E+06	7.4E+02	8.0E+07	5.0E+07	1.0E+08	6.8E+03
96		Nb	41						4.0E+07	1.0E+08	5.0E+07	1.4E+04
97		Nb	41	3.7E+05	3.3E+08	7.4E+04	3.3E+07	7.4E+03	8.0E+08	3.0E+09	1.0E+09	4.1E+05
98		Nb	41						5.0E+08	2.0E+09	6.2E+08	2.7E+05

1	2	3	4	5	6	7	8	9	10	11	12	13
90		Mo	42						7.0E+07	3.0E+08	8.7E+07	4.1E+04
93	m	Mo	42						2.0E+08	7.0E+08	2.5E+08	9.6E+04
93		Mo	42						1.0E+08	2.0E+08	1.2E+08	2.7E+04
99		Mo	42	3.0E+05	7.4E+07	1.1E+04	7.4E+06	1.1E+03	4.0E+07	1.0E+08	5.0E+07	1.4E+04
101		Mo	42						2.0E+09	5.0E+09	2.5E+09	6.8E+05
93	m	Tc	43						3.0E+09	6.0E+09	3.7E+09	8.2E+05
93		Tc	43						1.0E+09	3.0E+09	1.2E+09	4.1E+05
94	m	Tc	43						7.0E+08	2.0E+09	8.7E+08	2.7E+05
94		Tc	43						3.0E+08	7.0E+08	3.7E+08	9.6E+04
96	m	Tc	43	2.2E+06	3.7E+09	1.1E+06	3.7E+08	1.1E+05	6.0E+09	1.0E+10	7.5E+09	1.4E+06
96		Tc	43	3.7E+05	3.7E+07	7.4E+03	3.7E+06	7.4E+02	7.0E+07	1.0E+08	8.7E+07	1.4E+04
97	m	Tc	43	7.4E+05	1.5E+08	3.0E+04	1.5E+07	3.0E+03	2.0E+08	2.0E+08	2.5E+08	2.7E+04
97		Tc	43	2.2E+06	7.4E+08	1.5E+05	7.4E+07	1.5E+04	1.0E+09	2.0E+09	1.2E+09	2.7E+05
98		Tc	43						4.0E+07	6.0E+07	5.0E+07	8.2E+03
99	m	Tc	43	7.4E+06	2.2E+09	3.7E+05	2.2E+08	3.7E+04	3.0E+09	6.0E+09	3.7E+09	8.2E+05
99		Tc	43	3.7E+05	1.1E+08	2.6E+04	1.1E+07	2.6E+03	1.0E+08	2.0E+08	1.2E+08	2.7E+04
101		Tc	43						3.0E+09	1.0E+10	3.7E+09	1.4E+06
104		Tc	43						8.0E+08	3.0E+09	1.0E+09	4.1E+05
94		Ru	44						6.0E+08	2.0E+09	7.5E+08	2.7E+05
97		Ru	44	1.1E+06	1.5E+08	3.0E+04	1.5E+07	3.0E+03	3.0E+08	7.0E+08	3.7E+08	9.6E+04
103		Ru	44	7.4E+05	3.0E+07	7.4E+03	3.0E+06	7.4E+02	7.0E+07	6.0E+07	8.7E+07	8.2E+03
105		Ru	44	7.4E+04	3.7E+07	7.4E+03	3.7E+06	7.4E+02	2.0E+08	5.0E+08	2.5E+08	6.8E+04
106		Ru	44	1.1E+05	3.7E+06	1.1E+03	3.7E+05	1.1E+02	7.0E+06	3.0E+06	8.7E+06	4.1E+02
99	m	Rh	45						7.0E+08	2.0E+09	8.7E+08	2.7E+05
99		Rh	45						9.0E+07	1.0E+08	1.1E+08	1.4E+04
100		Rh	45						6.0E+07	2.0E+08	7.5E+07	2.7E+04
101	m	Rh	45						2.0E+08	4.0E+08	2.5E+08	5.5E+04
101		Rh	45						8.0E+07	2.0E+07	1.0E+08	2.7E+03
102	m	Rh	45						5.0E+07	2.0E+07	6.2E+07	2.7E+03
102		Rh	45						2.0E+07	3.0E+06	2.5E+07	4.1E+02
103	m	Rh	45	7.4E+06	3.7E+09	1.1E+06	3.7E+08	1.1E+05	2.0E+10	4.0E+10	2.5E+10	5.5E+06
105		Rh	45	1.5E+06	3.7E+07	1.1E+04	3.7E+06	1.1E+03	1.0E+08	4.0E+08	1.2E+08	5.5E+04
106	m	Rh	45						3.0E+08	9.0E+08	3.7E+08	1.2E+05
107		Rh	45						3.0E+09	9.0E+09	3.7E+09	1.2E+06
100		Pd	46						5.0E+07	5.0E+07	6.2E+07	6.8E+03
101		Pd	46						5.0E+08	1.0E+09	6.2E+08	1.4E+05
103		Pd	46	7.4E+05	1.1E+08	1.9E+04	1.1E+07	1.9E+03	2.0E+08	2.0E+08	2.5E+08	2.7E+04
107		Pd	46						1.0E+09	8.0E+08	1.2E+09	1.1E+05
109		Pd	46	2.6E+05	3.3E+07	7.4E+03	3.3E+06	7.4E+02	9.0E+07	2.0E+08	1.1E+08	2.7E+04
102		Ag	47						2.0E+09	7.0E+09	2.5E+09	9.6E+05
103		Ag	47						1.0E+09	4.0E+09	1.2E+09	5.5E+05
104	m	Ag	47						1.0E+09	4.0E+09	1.2E+09	5.5E+05
104		Ag	47						8.0E+08	3.0E+09	1.0E+09	4.1E+05
105		Ag	47	1.1E+06	3.7E+07	7.4E+03	3.7E+06	7.4E+02	1.0E+08	4.0E+07	1.2E+08	5.5E+03
106	m	Ag	47						3.0E+07	3.0E+07	3.7E+07	4.1E+03
106		Ag	47						2.0E+09	7.0E+09	2.5E+09	9.6E+05
108	m	Ag	47						2.0E+07	7.0E+06	2.5E+07	9.6E+02
110	m	Ag	47	3.7E+05	1.1E+07	2.6E+03	1.1E+06	2.6E+02	2.0E+07	5.0E+06	2.5E+07	6.8E+02
111		Ag	47	7.4E+05	1.5E+07	3.7E+03	1.5E+06	3.7E+02	3.0E+07	6.0E+07	3.7E+07	8.2E+03
112		Ag	47						1.0E+08	3.0E+08	1.2E+08	4.1E+04
115		Ag	47						1.0E+09	3.0E+09	1.2E+09	4.1E+05
104		Cd	48						8.0E+08	2.0E+09	1.0E+09	2.7E+05
107		Cd	48						8.0E+08	2.0E+09	1.0E+09	2.7E+05
109		Cd	48	7.4E+05	7.4E+07	7.4E+02	7.4E+06	7.4E+01	1.0E+07	1.0E+06	1.2E+07	1.4E+02
113	m	Cd	48						9.0E+05	9.0E+04	1.1E+06	1.2E+01
113		Cd	48						8.0E+05	8.0E+04	1.0E+06	1.1E+01
115	m	Cd	48	1.1E+05	1.1E+07	3.7E+02	1.1E+06	3.7E+01	1.0E+07	2.0E+06	1.2E+07	2.7E+02
115		Cd	48	1.1E+05	1.1E+07	3.0E+03	1.1E+06	3.0E+02	3.0E+07	5.0E+07	3.7E+07	6.8E+03
117	m	Cd	48						2.0E+08	5.0E+08	2.5E+08	6.8E+04

1	2	3	4	5	6	7	8	9	10	11	12	13
117		Cd	48						2.0E+08	4.0E+08	2.5E+08	5.5E+04
109		In	49						7.0E+08	2.0E+09	8.7E+08	2.7E+05
110	a	In	49						6.0E+08	2.0E+09	7.5E+08	2.7E+05
110	b	In	49						2.0E+08	6.0E+08	2.5E+08	8.2E+04
111		In	49						2.0E+08	2.0E+08	2.5E+08	2.7E+04
112		In	49						6.0E+09	2.0E+10	7.5E+09	2.7E+06
113	m	In	49	1.1E+06	3.7E+08	1.1E+05	3.7E+07	1.1E+04	2.0E+09	5.0E+09	2.5E+09	6.8E+05
114	m	In	49	2.2E+05	7.4E+06	1.5E+03	7.4E+05	1.5E+02	1.0E+07	2.0E+06	1.2E+07	2.7E+02
115	m	In	49	1.1E+06	1.5E+08	3.0E+04	1.5E+07	3.0E+03	5.0E+08	2.0E+09	6.2E+08	2.7E+05
115		In	49	1.1E+06	3.3E+07	3.3E+03	3.3E+06	3.3E+02	1.0E+06	5.0E+04	1.2E+06	6.8E+00
116	m	In	49						9.0E+08	3.0E+09	1.1E+09	4.1E+05
117	m	In	49						4.0E+08	1.0E+09	5.0E+08	1.4E+05
117		In	49						2.0E+09	6.0E+09	2.5E+09	8.2E+05
119	m	In	49						1.0E+09	5.0E+09	1.2E+09	6.8E+05
110		Sn	50						1.0E+08	4.0E+08	1.2E+08	5.5E+04
111		Sn	50						3.0E+09	8.0E+09	3.7E+09	1.1E+06
113		Sn	50	1.1E+06	3.3E+07	3.7E+03	3.3E+06	3.7E+02	6.0E+07	5.0E+07	7.5E+07	6.8E+03
117	m	Sn	50						6.0E+07	5.0E+07	7.5E+07	6.8E+03
119	m	Sn	50						1.0E+08	9.0E+07	1.2E+08	1.2E+04
121	m	Sn	50						1.0E+08	3.0E+07	1.2E+08	4.1E+03
121		Sn	50						2.0E+08	6.0E+08	2.5E+08	8.2E+04
123	m	Sn	50						2.0E+09	4.0E+09	2.5E+09	5.5E+05
123		Sn	50						2.0E+07	2.0E+07	2.5E+07	2.7E+03
125		Sn	50	2.6E+05	7.4E+06	1.5E+03	7.4E+05	1.5E+02	1.0E+07	3.0E+07	1.2E+07	4.1E+03
126		Sn	50						1.0E+07	2.0E+06	1.2E+07	2.7E+02
127		Sn	50						3.0E+08	7.0E+08	3.7E+08	9.6E+04
128		Sn	50						4.0E+08	1.0E+09	5.0E+08	1.4E+05
115		Sb	51						3.0E+09	9.0E+09	3.7E+09	1.2E+06
116	m	Sb	51						8.0E+08	3.0E+09	1.0E+09	4.1E+05
116		Sb	51						3.0E+09	1.0E+10	3.7E+09	1.4E+06
117		Sb	51						3.0E+09	8.0E+09	3.7E+09	1.1E+06
118	m	Sb	51						2.0E+08	7.0E+08	2.5E+08	9.6E+04
119		Sb	51						5.0E+08	2.0E+09	6.2E+08	2.7E+05
120	m	Sb	51						3.0E+07	8.0E+07	3.7E+07	1.1E+04
120		Sb	51						4.0E+09	2.0E+10	5.0E+09	2.7E+06
122		Sb	51	7.4E+05	1.1E+07	2.2E+03	1.1E+06	2.2E+02	3.0E+07	9.0E+07	3.7E+07	1.2E+04
124	m	Sb	51						9.0E+09	3.0E+10	1.1E+10	4.1E+06
124		Sb	51	3.7E+05	7.4E+06	1.9E+03	7.4E+05	1.9E+02	2.0E+07	3.0E+07	2.5E+07	4.1E+03
125		Sb	51	1.5E+06	3.7E+07	7.4E+03	3.7E+06	7.4E+02	7.0E+07	9.0E+07	8.7E+07	1.2E+04
126	m	Sb	51						2.0E+09	7.0E+09	2.5E+09	9.6E+05
126		Sb	51						2.0E+07	4.0E+07	2.5E+07	5.5E+03
127		Sb	51						3.0E+07	8.0E+07	3.7E+07	1.1E+04
128	m	Sb	51						3.0E+09	1.0E+10	3.7E+09	1.4E+06
128		Sb	51						4.0E+07	2.0E+08	5.0E+07	2.7E+04
129		Sb	51						1.0E+08	3.0E+08	1.2E+08	4.1E+04
130		Sb	51						7.0E+08	2.0E+09	8.7E+08	2.7E+05
131		Sb	51						6.0E+08	9.0E+08	7.5E+08	1.2E+05
116		Te	52						3.0E+08	8.0E+08	3.7E+08	1.1E+05
121	m	Te	52						2.0E+07	7.0E+06	2.5E+07	9.6E+02
121		Te	52						1.0E+08	2.0E+08	1.2E+08	2.7E+04
123	m	Te	52						2.0E+07	8.0E+06	2.5E+07	1.1E+03
123		Te	52						2.0E+07	7.0E+06	2.5E+07	9.6E+02
125	m	Te	52	7.4E+05	7.4E+07	3.7E+03	1.5E+07	3.7E+02	4.0E+07	2.0E+07	5.0E+07	2.7E+03
127	m	Te	52	2.6E+05	2.2E+07	1.9E+03	2.2E+06	1.9E+02	2.0E+07	1.0E+07	2.5E+07	1.4E+03
127		Te	52	7.4E+05	1.1E+08	2.2E+04	1.1E+07	2.2E+03	3.0E+08	8.0E+08	3.7E+08	1.1E+05
129	m	Te	52	1.1E+05	1.1E+07	1.1E+03	1.1E+06	1.1E+02	2.0E+07	2.0E+07	2.5E+07	2.7E+03
129		Te	52	1.9E+05	3.0E+08	7.4E+04	3.0E+07	7.4E+03	1.0E+09	2.0E+09	1.2E+09	2.7E+05
131	m	Te	52	1.5E+05	2.2E+07	3.7E+03	2.2E+06	3.7E+02	1.0E+07	2.0E+07	1.2E+07	2.7E+03
131		Te	52						1.0E+08	2.0E+08	1.2E+08	2.7E+04

1	2	3	4	5	6	7	8	9	10	11	12	13
132		Te	52	1.1E+05	1.1E+07	2.6E+03	1.1E+06	2.6E+02	8.0E+06	9.0E+06	1.0E+07	1.2E+03
133	m	Te	52						1.0E+08	2.0E+08	1.2E+08	2.7E+04
133		Te	52						5.0E+08	8.0E+08	6.2E+08	1.1E+05
134		Te	52						6.0E+08	9.0E+08	7.5E+08	1.2E+05
120	m	I	53						4.0E+08	8.0E+08	5.0E+08	1.1E+05
120		I	53						1.0E+08	3.0E+08	1.2E+08	4.1E+04
121		I	53						4.0E+08	7.0E+08	5.0E+08	9.6E+04
123		I	53						1.0E+08	2.0E+08	1.2E+08	2.7E+04
124		I	53						2.0E+06	3.0E+06	2.5E+06	4.1E+02
125		I	53				7.4E+03	3.0E+00	1.0E+06	2.0E+06	1.2E+06	2.7E+02
126		I	53	3.7E+04	7.4E+05	1.1E+02	1.1E+04	3.3E+00	8.0E+05	1.0E+06	1.0E+06	1.4E+02
128		I	53						2.0E+09	4.0E+09	2.5E+09	5.5E+05
129		I	53	1.1E+05	1.5E+05	2.2E+01	2.2E+03	7.4E-01	2.0E+05	3.0E+05	2.5E+05	4.1E+01
130		I	53						1.0E+07	3.0E+07	1.2E+07	4.1E+03
131		I	53	2.6E+04	7.4E+05	1.1E+02	1.1E+04	3.7E+00	1.0E+06	2.0E+06	1.2E+06	2.7E+02
132	m	I	53						1.0E+08	3.0E+08	1.2E+08	4.1E+04
132		I	53	1.1E+04	2.2E+07	3.0E+03	3.0E+05	1.1E+02	1.0E+08	3.0E+08	1.2E+08	4.1E+04
133		I	53	1.1E+04	2.6E+06	3.7E+02	3.7E+04	1.5E+01	5.0E+06	1.0E+07	6.2E+06	1.4E+03
134		I	53	7.4E+03	3.7E+07	7.4E+03	7.4E+05	2.2E+02	8.0E+08	2.0E+09	1.0E+09	2.7E+05
135		I	53	1.1E+04	7.4E+06	1.5E+03	1.5E+05	3.7E+01	3.0E+07	6.0E+07	3.7E+07	8.2E+03
131	m	Xe	54			1.5E+05		1.5E+04				
133	m	Xe	54					1.1E+04				
133		Xe	54			1.1E+05		1.1E+04				
135		Xe	54			3.7E+04		3.7E+03				
125		Cs	55						2.0E+09	5.0E+09	2.5E+09	6.8E+05
127		Cs	55						2.0E+09	4.0E+09	2.5E+09	5.5E+05
129		Cs	55						9.0E+08	1.0E+09	1.1E+09	1.4E+05
130		Cs	55						2.0E+09	7.0E+09	2.5E+09	9.6E+05
131		Cs	55	2.6E+07	7.4E+08	1.5E+05	7.4E+07	1.5E+04	8.0E+08	1.0E+09	1.0E+09	1.4E+05
132		Cs	55						1.0E+08	1.0E+08	1.2E+08	1.4E+04
134	m	Cs	55	3.7E+06	2.2E+09	3.7E+05	2.2E+08	3.7E+04	4.0E+09	5.0E+09	5.0E+09	6.8E+05
134		Cs	55	7.4E+05	3.3E+06	3.7E+02	3.3E+05	3.7E+01	3.0E+06	4.0E+06	3.7E+06	5.5E+02
135	m	Cs	55						4.0E+09	7.0E+09	5.0E+09	9.6E+05
135		Cs	55	7.4E+06	3.7E+07	7.4E+03	3.7E+06	7.4E+02	3.0E+07	4.0E+07	3.7E+07	5.5E+03
136		Cs	55	1.1E+06	3.3E+07	3.7E+03	3.3E+06	3.7E+02	2.0E+07	2.0E+07	2.5E+07	2.7E+03
137		Cs	55	1.1E+06	7.4E+06	7.4E+02	7.4E+05	7.4E+01	4.0E+06	6.0E+06	5.0E+06	8.2E+02
138		Cs	55						7.0E+08	2.0E+09	8.7E+08	2.7E+05
126		Ba	56						2.0E+08	6.0E+08	2.5E+08	8.2E+04
128		Ba	56						2.0E+07	7.0E+07	2.5E+07	9.6E+03
131	m	Ba	56						1.0E+10	5.0E+10	1.2E+10	6.8E+06
131		Ba	56	1.9E+06	7.4E+07	1.5E+04	7.4E+06	1.5E+03	1.0E+08	3.0E+08	1.2E+08	4.1E+04
133	m	Ba	56						9.0E+07	3.0E+08	1.1E+08	4.1E+04
133		Ba	56						6.0E+07	3.0E+07	7.5E+07	4.1E+03
135	m	Ba	56						1.0E+08	4.0E+08	1.2E+08	5.5E+04
139		Ba	56						5.0E+08	1.0E+09	6.2E+08	1.4E+05
140		Ba	56	1.5E+05	1.1E+07	1.5E+03	1.1E+06	1.5E+02	2.0E+07	5.0E+07	2.5E+07	6.8E+03
141		Ba	56						9.0E+08	3.0E+09	1.1E+09	4.1E+05
142		Ba	56						2.0E+09	5.0E+09	2.5E+09	6.8E+05
131		La	57						2.0E+09	4.0E+09	2.5E+09	5.5E+05
132		La	57						1.0E+08	4.0E+08	1.2E+08	5.5E+04
135		La	57						1.0E+09	4.0E+09	1.2E+09	5.5E+05
137		La	57						4.0E+08	2.0E+06	5.0E+08	2.7E+02
138		La	57						3.0E+07	1.0E+05	3.7E+07	1.4E+01
140		La	57	3.3E+05	7.4E+06	1.9E+03	7.4E+05	1.9E+02	2.0E+07	5.0E+07	2.5E+07	6.8E+03
141		La	57						1.0E+08	3.0E+08	1.2E+08	4.1E+04
142		La	57						3.0E+08	8.0E+08	3.7E+08	1.1E+05
143		La	57						1.0E+09	4.0E+09	1.2E+09	5.5E+05
134		Ce	58						2.0E+07	3.0E+07	2.5E+07	4.1E+03
135		Ce	58						6.0E+07	1.0E+08	7.5E+07	1.4E+04

1	2	3	4	5	6	7	8	9	10	11	12	13
137	m	Ce	58						9.0E+07	2.0E+08	1.1E+08	2.7E+04
137		Ce	58						2.0E+09	5.0E+09	2.5E+09	6.8E+05
139		Ce	58						2.0E+08	3.0E+07	2.5E+08	4.1E+03
141		Ce	58	1.1E+06	3.3E+07	7.4E+03	3.3E+06	7.4E+02	6.0E+07	3.0E+07	7.5E+07	4.1E+03
143		Ce	58	2.6E+05	1.5E+07	3.3E+03	1.5E+06	3.3E+02	4.0E+07	7.0E+07	5.0E+07	9.6E+03
144		Ce	58	1.9E+05	3.7E+06	1.1E+02	3.7E+05	1.1E+01	8.0E+06	9.0E+05	1.0E+07	1.2E+02
136		Pr	59						2.0E+09	9.0E+09	2.5E+09	1.2E+06
137		Pr	59						1.0E+09	6.0E+09	1.2E+09	8.2E+05
138	m	Pr	59						4.0E+08	2.0E+09	5.0E+08	2.7E+05
139		Pr	59						1.0E+09	4.0E+09	1.2E+09	5.5E+05
142	m	Pr	59						3.0E+09	6.0E+09	3.7E+09	8.2E+05
142		Pr	59	2.6E+05	1.1E+07	2.6E+03	1.1E+06	2.6E+02	4.0E+07	8.0E+07	5.0E+07	1.1E+04
143		Pr	59	7.4E+05	1.9E+07	3.7E+03	1.9E+06	3.7E+02	3.0E+07	3.0E+07	3.7E+07	4.1E+03
144		Pr	59						1.0E+09	5.0E+09	1.2E+09	6.8E+05
145		Pr	59						1.0E+08	3.0E+08	1.2E+08	4.1E+04
147		Pr	59						2.0E+09	7.0E+09	2.5E+09	9.6E+05
136		Nd	60						6.0E+08	2.0E+09	7.5E+08	2.7E+05
138		Nd	60						7.0E+07	2.0E+08	8.7E+07	2.7E+04
139	m	Nd	60						2.0E+08	6.0E+08	2.5E+08	8.2E+04
139		Nd	60						3.0E+09	1.0E+10	3.7E+09	1.4E+06
141		Nd	60						6.0E+09	3.0E+10	7.5E+09	4.1E+06
144		Nd	60	3.7E+03	2.6E+07	1.1E+00	2.6E+06	1.1E-01				
147		Nd	60	3.7E+05	2.2E+07	3.7E+03	2.2E+06	3.7E+02	4.0E+07	3.0E+07	5.0E+07	4.1E+03
149		Nd	60	1.1E+05	1.1E+08	2.2E+04	1.1E+07	2.2E+03	4.0E+08	1.0E+09	5.0E+08	1.4E+05
151		Nd	60						3.0E+09	7.0E+09	3.7E+09	9.6E+05
141		Pm	61						2.0E+09	7.0E+09	2.5E+09	9.6E+05
143		Pm	61						2.0E+08	2.0E+07	2.5E+08	2.7E+03
144		Pm	61						5.0E+07	4.0E+06	6.2E+07	5.5E+02
145		Pm	61						4.0E+08	7.0E+06	5.0E+08	9.6E+02
146		Pm	61						6.0E+07	2.0E+06	7.5E+07	2.7E+02
147		Pm	61	2.2E+06	7.4E+07	7.4E+02	7.4E+06	7.4E+01	2.0E+08	5.0E+06	2.5E+08	6.8E+02
148	m	Pm	61						3.0E+07	1.0E+07	3.7E+07	1.4E+03
148		Pm	61						2.0E+07	2.0E+07	2.5E+07	2.7E+03
149		Pm	61	7.4E+05	1.5E+07	3.7E+03	1.5E+06	3.7E+02	4.0E+07	7.0E+07	5.0E+07	9.6E+03
150		Pm	61						2.0E+08	7.0E+08	2.5E+08	9.6E+04
151		Pm	61						7.0E+07	1.0E+08	8.7E+07	1.4E+04
141	m	Sm	62						1.0E+09	4.0E+09	1.2E+09	5.5E+05
141		Sm	62						2.0E+09	7.0E+09	2.5E+09	9.6E+05
142		Sm	62						3.0E+08	1.0E+09	3.7E+08	1.4E+05
145		Sm	62						2.0E+08	2.0E+07	2.5E+08	2.7E+03
146		Sm	62						5.0E+05	1.0E+03	6.2E+05	1.4E-01
147		Sm	62	3.7E+03	2.2E+07	7.4E-01	2.2E+06	7.4E-02	6.0E+05	1.0E+03	7.5E+05	1.4E-01
151		Sm	62	3.7E+06	1.5E+08	7.4E+02	1.5E+07	7.4E+01	5.0E+08	4.0E+06	6.2E+08	5.5E+02
153		Sm	62	7.4E+05	3.0E+07	7.4E+03	3.0E+06	7.4E+02	6.0E+07	1.0E+08	7.5E+07	1.4E+04
155		Sm	62						2.0E+09	8.0E+09	2.5E+09	1.1E+06
156		Sm	62						2.0E+08	3.0E+08	2.5E+08	4.1E+04
145		Eu	63						6.0E+07	7.0E+07	7.5E+07	9.6E+03
146		Eu	63						4.0E+07	5.0E+07	5.0E+07	6.8E+03
147		Eu	63						1.0E+08	6.0E+07	1.2E+08	8.2E+03
148		Eu	63						4.0E+07	1.0E+07	5.0E+07	1.4E+03
149		Eu	63						4.0E+08	1.0E+08	5.0E+08	1.4E+04
150	m	Eu	63						3.0E+07	7.0E+05	3.7E+07	9.6E+01
150		Eu	63						1.0E+08	3.0E+08	1.2E+08	4.1E+04
152	m	Eu	63	3.0E+05	2.2E+07	3.7E+03	2.2E+06	3.7E+02	1.0E+08	2.0E+08	1.2E+08	2.7E+04
152		Eu	63	7.4E+05	3.0E+07	1.5E+02	3.0E+06	1.5E+01	3.0E+07	9.0E+05	3.7E+07	1.2E+02
154		Eu	63	1.9E+05	7.4E+06	3.7E+01	7.4E+05	3.7E+00	2.0E+07	7.0E+05	2.5E+07	9.6E+01
155		Eu	63	2.6E+06	7.4E+07	1.1E+03	7.4E+06	1.1E+02	1.0E+08	3.0E+06	1.2E+08	4.1E+02
156		Eu	63						2.0E+07	2.0E+07	2.5E+07	2.7E+03
157		Eu	63						8.0E+07	2.0E+08	1.0E+08	2.7E+04

1	2	3	4	5	6	7	8	9	10	11	12	13
158		Eu	63						7.0E+08	2.0E+09	8.7E+08	2.7E+05
145		Gd	64						2.0E+09	6.0E+09	2.5E+09	8.2E+05
146		Gd	64						5.0E+07	5.0E+06	6.2E+07	6.8E+02
147		Gd	64						7.0E+07	2.0E+08	8.7E+07	2.7E+04
148		Gd	64						4.0E+05	3.0E+02	5.0E+05	4.1E-02
149		Gd	64						1.0E+08	8.0E+07	1.2E+08	1.1E+04
151		Gd	64						2.0E+08	1.0E+07	2.5E+08	1.4E+03
152		Gd	64						6.0E+05	4.0E+02	7.5E+05	5.5E-02
153		Gd	64	3.3E+06	7.4E+07	3.0E+03	7.4E+06	3.0E+02	2.0E+08	5.0E+06	2.5E+08	6.8E+02
159		Gd	64	7.4E+05	3.0E+07	7.4E+03	3.0E+06	7.4E+02	1.0E+08	3.0E+08	1.2E+08	4.1E+04
147		Tb	65						3.0E+08	1.0E+09	3.7E+08	1.4E+05
149		Tb	65						2.0E+08	3.0E+07	2.5E+08	4.1E+03
150		Tb	65						2.0E+08	8.0E+08	2.5E+08	1.1E+05
151		Tb	65						1.0E+08	3.0E+08	1.2E+08	4.1E+04
153		Tb	65						2.0E+08	3.0E+08	2.5E+08	4.1E+04
154		Tb	65						6.0E+07	2.0E+08	7.5E+07	2.7E+04
155		Tb	65						2.0E+08	3.0E+08	2.5E+08	4.1E+04
156	m1	Tb	65						6.0E+08	1.0E+09	7.5E+08	1.4E+05
156	m2	Tb	65						3.0E+08	3.0E+08	3.7E+08	4.1E+04
156		Tb	65						4.0E+07	5.0E+07	5.0E+07	6.8E+03
157		Tb	65						2.0E+09	1.0E+07	2.5E+09	1.4E+03
158		Tb	65						5.0E+07	7.0E+05	6.2E+07	9.6E+01
160		Tb	65	7.4E+05	1.5E+07	1.1E+03	1.5E+06	1.1E+02	3.0E+07	8.0E+06	3.7E+07	1.1E+03
161		Tb	65						6.0E+07	6.0E+07	7.5E+07	8.2E+03
155		Dy	66						3.0E+08	9.0E+08	3.7E+08	1.2E+05
157		Dy	66						7.0E+08	2.0E+09	8.7E+08	2.7E+05
159		Dy	66						5.0E+08	9.0E+07	6.2E+08	1.2E+04
165		Dy	66	3.7E+05	1.5E+08	3.3E+04	1.5E+07	3.3E+03	5.0E+08	2.0E+09	6.2E+08	2.7E+05
166		Dy	66	1.9E+05	1.5E+07	3.0E+03	1.5E+06	3.0E+02	2.0E+07	3.0E+07	2.5E+07	4.1E+03
155		Ho	67						2.0E+09	6.0E+09	2.5E+09	8.2E+05
157		Ho	67						1.0E+10	5.0E+10	1.2E+10	6.8E+06
159		Ho	67						8.0E+09	4.0E+10	1.0E+10	5.5E+06
161		Ho	67						4.0E+09	2.0E+10	5.0E+09	2.7E+06
162	m	Ho	67						2.0E+09	1.0E+10	2.5E+09	1.4E+06
162		Ho	67						2.0E+10	9.0E+10	2.5E+10	1.2E+07
164	m	Ho	67						4.0E+09	1.0E+10	5.0E+09	1.4E+06
164		Ho	67						7.0E+09	2.0E+10	8.7E+09	2.7E+06
166	m	Ho	67						2.0E+07	3.0E+05	2.5E+07	4.1E+01
166		Ho	67	1.9E+05	1.1E+07	2.6E+03	1.1E+06	2.6E+02	3.0E+07	7.0E+07	3.7E+07	9.6E+03
167		Ho	67						6.0E+08	2.0E+09	7.5E+08	2.7E+05
161		Er	68						6.0E+08	2.0E+09	7.5E+08	2.7E+05
165		Er	68						2.0E+09	7.0E+09	2.5E+09	9.6E+05
169		Er	68	1.1E+06	3.3E+07	7.4E+03	3.3E+06	7.4E+02	1.0E+08	9.0E+07	1.2E+08	1.2E+04
171		Er	68	3.3E+05	3.7E+07	7.4E+03	3.7E+06	7.4E+02	1.0E+08	4.0E+08	1.2E+08	5.5E+04
172		Er	68						4.0E+07	5.0E+07	5.0E+07	6.8E+03
162		Tm	69						2.0E+09	1.0E+10	2.5E+09	1.4E+06
166		Tm	69						2.0E+08	5.0E+08	2.5E+08	6.8E+04
167		Tm	69						8.0E+07	7.0E+07	1.0E+08	9.6E+03
170		Tm	69	3.3E+05	1.9E+07	3.7E+02	1.9E+06	3.7E+01	3.0E+07	8.0E+06	3.7E+07	1.1E+03
171		Tm	69	3.3E+06	1.9E+08	1.5E+03	1.9E+07	1.5E+02	4.0E+08	1.0E+07	5.0E+08	1.4E+03
172		Tm	69						3.0E+07	4.0E+07	3.7E+07	5.5E+03
173		Tm	69						2.0E+08	4.0E+08	2.5E+08	5.5E+04
175		Tm	69						2.0E+09	1.0E+10	2.5E+09	1.4E+06
162		Yb	70						3.0E+09	1.0E+10	3.7E+09	1.4E+06
166		Yb	70						5.0E+07	7.0E+07	6.2E+07	9.6E+03
167		Yb	70						1.0E+10	3.0E+10	1.2E+10	4.1E+06
169		Yb	70						7.0E+07	3.0E+07	8.7E+07	4.1E+03
175		Yb	70	1.1E+06	3.7E+07	7.4E+03	3.7E+06	7.4E+02	1.0E+08	1.0E+08	1.2E+08	1.4E+04
177		Yb	70						6.0E+08	2.0E+09	7.5E+08	2.7E+05

1	2	3	4	5	6	7	8	9	10	11	12	13
178		Yb	70						5.0E+08	1.0E+09	6.2E+08	1.4E+05
169		Lu	71						9.0E+07	2.0E+08	1.1E+08	2.7E+04
170		Lu	71						4.0E+07	8.0E+07	5.0E+07	1.1E+04
171		Lu	71						7.0E+07	7.0E+07	8.7E+07	9.6E+03
172		Lu	71						4.0E+07	4.0E+07	5.0E+07	5.5E+03
173		Lu	71						2.0E+08	1.0E+07	2.5E+08	1.4E+03
174	m	Lu	71						8.0E+07	9.0E+06	1.0E+08	1.2E+03
174		Lu	71						2.0E+08	4.0E+06	2.5E+08	5.5E+02
176	m	Lu	71						3.0E+08	9.0E+08	3.7E+08	1.2E+05
176		Lu	71						3.0E+07	2.0E+05	3.7E+07	2.7E+01
177	m	Lu	71						3.0E+07	4.0E+06	3.7E+07	5.5E+02
177		Lu	71	7.4E+05	3.7E+07	7.4E+03	3.7E+06	7.4E+02	8.0E+07	8.0E+07	1.0E+08	1.1E+04
178	m	Lu	71						2.0E+09	7.0E+09	2.5E+09	9.6E+05
178		Lu	71						1.0E+09	5.0E+09	1.2E+09	6.8E+05
179		Lu	71						2.0E+08	7.0E+08	2.5E+08	9.6E+04
170		Hf	72						1.0E+08	2.0E+08	1.2E+08	2.7E+04
172		Hf	72						5.0E+07	3.0E+05	6.2E+07	4.1E+01
173		Hf	72						2.0E+08	5.0E+08	2.5E+08	6.8E+04
175		Hf	72						1.0E+08	4.0E+07	1.2E+08	5.5E+03
177	m	Hf	72						7.0E+08	2.0E+09	8.7E+08	2.7E+05
178	m	Hf	72						9.0E+06	5.0E+04	1.1E+07	6.8E+00
179	m	Hf	72						4.0E+07	1.0E+07	5.0E+07	1.4E+03
180	m	Hf	72						3.0E+08	8.0E+08	3.7E+08	1.1E+05
181		Hf	72	1.5E+05	2.6E+07	3.7E+02	2.6E+06	3.7E+01	4.0E+07	6.0E+06	5.0E+07	8.2E+02
182	m	Hf	72						1.0E+09	3.0E+09	1.2E+09	4.1E+05
182		Hf	72						7.0E+06	3.0E+04	8.7E+06	4.1E+00
183		Hf	72						8.0E+08	2.0E+09	1.0E+09	2.7E+05
184		Hf	72						9.0E+07	3.0E+08	1.1E+08	4.1E+04
172		Ta	73						1.0E+09	5.0E+09	1.2E+09	6.8E+05
173		Ta	73						2.0E+08	7.0E+08	2.5E+08	9.6E+04
174		Ta	73						1.0E+09	4.0E+09	1.2E+09	5.5E+05
175		Ta	73						2.0E+08	6.0E+08	2.5E+08	8.2E+04
176		Ta	73						1.0E+08	5.0E+08	1.2E+08	6.8E+04
177		Ta	73						4.0E+08	7.0E+08	5.0E+08	9.6E+04
178		Ta	73						6.0E+08	3.0E+09	7.5E+08	4.1E+05
179		Ta	73						8.0E+08	2.0E+08	1.0E+09	2.7E+04
180	m	Ta	73						9.0E+08	2.0E+09	1.1E+09	2.7E+05
180		Ta	73						6.0E+07	2.0E+07	7.5E+07	2.7E+03
182	m	Ta	73						6.0E+09	2.0E+10	7.5E+09	2.7E+06
182		Ta	73	2.6E+05	1.5E+07	3.7E+02	1.5E+06	3.7E+01	3.0E+07	1.0E+07	3.7E+07	1.4E+03
183		Ta	73						3.0E+07	4.0E+07	3.7E+07	5.5E+03
184		Ta	73						7.0E+07	2.0E+08	8.7E+07	2.7E+04
185		Ta	73						1.0E+09	3.0E+09	1.2E+09	4.1E+05
186		Ta	73						2.0E+09	9.0E+09	2.5E+09	1.2E+06
176		W	74						4.0E+08	2.0E+09	5.0E+08	2.7E+05
177		W	74						8.0E+08	3.0E+09	1.0E+09	4.1E+05
178		W	74						2.0E+08	7.0E+08	2.5E+08	9.6E+04
179		W	74						2.0E+10	6.0E+10	2.5E+10	8.2E+06
181		W	74	2.6E+06	1.5E+08	3.0E+04	1.5E+07	3.0E+03	6.0E+08	1.0E+09	7.5E+08	1.4E+05
185		W	74	1.1E+06	3.7E+07	1.1E+04	3.7E+06	1.1E+03	8.0E+07	2.0E+08	1.0E+08	2.7E+04
187		W	74	1.1E+06	2.6E+07	7.4E+03	2.6E+06	7.4E+02	7.0E+07	3.0E+08	8.7E+07	4.1E+04
188		W	74						1.0E+07	5.0E+07	1.2E+07	6.8E+03
177		Re	75						4.0E+09	1.0E+10	5.0E+09	1.4E+06
178		Re	75						3.0E+09	1.0E+10	3.7E+09	1.4E+06
181		Re	75						2.0E+08	3.0E+08	2.5E+08	4.1E+04
182	a	Re	75						5.0E+07	9.0E+07	6.2E+07	1.2E+04
182	b	Re	75						3.0E+08	5.0E+08	3.7E+08	6.8E+04
183		Re	75	3.0E+06	2.2E+08	3.3E+04	2.2E+07	3.3E+03				
184	m	Re	75						8.0E+07	1.0E+08	1.0E+08	1.4E+04

1	2	3	4	5	6	7	8	9	10	11	12	13
184		Re	75						9.0E+07	1.0E+08	1.1E+08	1.4E+04
186	m	Re	75						5.0E+07	6.0E+07	6.2E+07	8.2E+03
186		Re	75	7.4E+05	3.3E+07	7.4E+03	3.3E+06	7.4E+02	7.0E+07	1.0E+08	8.7E+07	1.4E+04
187		Re	75	1.1E+07	1.1E+09	1.1E+05	1.1E+08	1.1E+04	2.0E+10	3.0E+10	2.5E+10	4.1E+06
188	m	Re	75						3.0E+09	5.0E+09	3.7E+09	6.8E+05
188		Re	75	2.6E+05	2.2E+07	3.7E+03	2.2E+06	3.7E+02	6.0E+07	1.0E+08	7.5E+07	1.4E+04
189		Re	75						1.0E+08	2.0E+08	1.2E+08	2.7E+04
180		Os	76						4.0E+09	1.0E+10	5.0E+09	1.4E+06
181		Os	76						5.0E+08	2.0E+09	6.2E+08	2.7E+05
182		Os	76						8.0E+07	2.0E+08	1.0E+08	2.7E+04
185		Os	76	3.0E+05	2.6E+07	7.4E+03	2.6E+06	7.4E+02	9.0E+07	2.0E+07	1.1E+08	2.7E+03
189	m	Os	76						3.0E+09	9.0E+09	3.7E+09	1.2E+06
191	m	Os	76	3.7E+06	1.1E+09	2.2E+05	1.1E+08	2.2E+04	5.0E+08	1.0E+09	6.2E+08	1.4E+05
191		Os	76	7.4E+05	7.4E+07	1.5E+04	7.4E+06	1.5E+03	8.0E+07	8.0E+07	1.0E+08	1.1E+04
193		Os	76	3.7E+05	2.2E+07	3.7E+03	2.2E+06	3.7E+02	6.0E+07	2.0E+08	7.5E+07	2.7E+04
194		Os	76						2.0E+07	2.0E+06	2.5E+07	2.7E+02
182		Ir	77						2.0E+09	5.0E+09	2.5E+09	6.8E+05
184		Ir	77						3.0E+08	9.0E+08	3.7E+08	1.2E+05
185		Ir	77						2.0E+08	5.0E+08	2.5E+08	6.8E+04
186		Ir	77						9.0E+07	3.0E+08	1.1E+08	4.1E+04
187		Ir	77						4.0E+08	1.0E+09	5.0E+08	1.4E+05
188		Ir	77						7.0E+07	2.0E+08	8.7E+07	2.7E+04
189		Ir	77						2.0E+08	2.0E+08	2.5E+08	2.7E+04
190	m	Ir	77						6.0E+09	7.0E+09	7.5E+09	9.6E+05
190		Ir	77	1.5E+06	7.4E+07	1.5E+04	7.4E+06	1.5E+03	4.0E+07	3.0E+07	5.0E+07	4.1E+03
192	m	Ir	77						1.0E+08	3.0E+06	1.2E+08	4.1E+02
192		Ir	77	2.2E+05	1.5E+07	1.5E+03	1.5E+06	1.5E+02	4.0E+07	1.0E+07	5.0E+07	1.4E+03
194	m	Ir	77						2.0E+07	3.0E+06	2.5E+07	4.1E+02
194		Ir	77	2.6E+05	1.1E+07	3.0E+03	1.1E+06	3.0E+02	4.0E+07	1.0E+08	5.0E+07	1.4E+04
195	m	Ir	77						3.0E+08	9.0E+08	3.7E+08	1.2E+05
195		Ir	77						6.0E+08	2.0E+09	7.5E+08	2.7E+05
186		Pt	78						5.0E+08	1.0E+09	6.2E+08	1.4E+05
188		Pt	78						6.0E+07	6.0E+07	7.5E+07	8.2E+03
189		Pt	78						4.0E+08	1.0E+09	5.0E+08	1.4E+05
191		Pt	78	3.7E+05	3.7E+07	1.1E+04	3.7E+06	1.1E+03	1.0E+08	3.0E+08	1.2E+08	4.1E+04
193	m	Pt	78	3.7E+06	3.7E+08	7.4E+04	3.7E+07	7.4E+03	9.0E+07	2.0E+08	1.1E+08	2.7E+04
193		Pt	78	2.6E+06	3.3E+08	1.5E+04			1.0E+09	9.0E+08	1.2E+09	1.2E+05
195	m	Pt	78						7.0E+07	2.0E+08	8.7E+07	2.7E+04
197	m	Pt	78	1.9E+05	3.7E+08	7.4E+04	3.7E+07	7.4E+03	6.0E+08	2.0E+09	7.5E+08	2.7E+05
197		Pt	78	3.7E+05	3.7E+07	1.1E+04	3.7E+06	1.1E+03	1.0E+08	4.0E+08	1.2E+08	5.5E+04
199		Pt	78						2.0E+09	5.0E+09	2.5E+09	6.8E+05
200		Pt	78						4.0E+07	1.0E+08	5.0E+07	1.4E+04
193		Au	79						3.0E+08	1.0E+09	3.7E+08	1.4E+05
194		Au	79						1.0E+08	3.0E+08	1.2E+08	4.1E+04
195		Au	79						2.0E+08	4.0E+08	2.5E+08	5.5E+04
196		Au	79	1.5E+06	7.4E+07	1.5E+04	7.4E+06	1.5E+03				
198	m	Au	79						4.0E+07	1.0E+08	5.0E+07	1.4E+04
198		Au	79	7.4E+05	1.9E+07	3.7E+03	1.9E+06	3.7E+02	5.0E+07	1.0E+08	6.2E+07	1.4E+04
199		Au	79	2.6E+06	7.4E+07	1.5E+04	7.4E+06	1.5E+03	1.0E+08	3.0E+08	1.2E+08	4.1E+04
200	m	Au	79						4.0E+07	1.0E+08	5.0E+07	1.4E+04
200		Au	79						1.0E+09	2.0E+09	1.2E+09	2.7E+05
201		Au	79						3.0E+09	8.0E+09	3.7E+09	1.1E+06
193	m	Hg	80						1.0E+08	3.0E+08	1.2E+08	4.1E+04
193		Hg	80						6.0E+08	2.0E+09	7.5E+08	2.7E+05
194		Hg	80						3.0E+07	2.0E+06	3.7E+07	2.7E+02
195	m	Hg	80						9.0E+07	2.0E+08	1.1E+08	2.7E+04
195		Hg	80						5.0E+08	1.0E+09	6.2E+08	1.4E+05
197	m	Hg	80	1.5E+05	7.4E+07	1.1E+04	7.4E+06	1.1E+03	1.0E+08	3.0E+08	1.2E+08	4.1E+04
197		Hg	80	7.4E+05	1.1E+08	1.5E+04	1.1E+07	1.5E+03	2.0E+08	4.0E+08	2.5E+08	5.5E+04

1	2	3	4	5	6	7	8	9	10	11	12	13
199	m	Hg	80						2.0E+09	5.0E+09	2.5E+09	6.8E+05
203		Hg	80	1.5E+05	7.4E+06	7.4E+02	7.4E+05	7.4E+01	9.0E+07	5.0E+07	1.1E+08	6.8E+03
194	m	Tl	81						2.0E+09	6.0E+09	2.5E+09	8.2E+05
194		Tl	81						9.0E+09	2.0E+10	1.1E+10	2.7E+06
195		Tl	81						2.0E+09	5.0E+09	2.5E+09	6.8E+05
197		Tl	81						3.0E+09	4.0E+09	3.7E+09	5.5E+05
198	m	Tl	81						1.0E+09	2.0E+09	1.2E+09	2.7E+05
198		Tl	81						7.0E+08	1.0E+09	8.7E+08	1.4E+05
199		Tl	81						2.0E+09	3.0E+09	2.5E+09	4.1E+05
200		Tl	81	1.5E+06	1.5E+08	3.3E+04	1.5E+07	3.3E+03	3.0E+08	4.0E+08	3.7E+08	5.5E+04
201		Tl	81	1.5E+06	1.1E+08	2.6E+04	1.1E+07	2.6E+03	6.0E+08	8.0E+08	7.5E+08	1.1E+05
202		Tl	81	7.4E+05	3.7E+07	1.1E+04	3.7E+06	1.1E+03	1.0E+08	2.0E+08	1.2E+08	2.7E+04
204		Tl	81	3.7E+05	3.7E+07	7.4E+03	3.7E+06	7.4E+02	6.0E+07	8.0E+07	7.5E+07	1.1E+04
195	m	Pb	82						2.0E+09	7.0E+09	2.5E+09	9.6E+05
198		Pb	82						1.0E+09	2.0E+09	1.2E+09	2.7E+05
199		Pb	82						8.0E+08	3.0E+09	1.0E+09	4.1E+05
200		Pb	82						1.0E+08	2.0E+08	1.2E+08	2.7E+04
201		Pb	82						3.0E+08	7.0E+08	3.7E+08	9.6E+04
202	m	Pb	82						3.0E+08	1.0E+09	3.7E+08	1.4E+05
202		Pb	82						5.0E+06	2.0E+06	6.2E+06	2.7E+02
203		Pb	82	1.1E+06	1.5E+08	3.3E+04	1.5E+07	3.3E+03	2.0E+08	4.0E+08	2.5E+08	5.5E+04
205		Pb	82						1.0E+08	5.0E+07	1.2E+08	6.8E+03
209		Pb	82						9.0E+08	2.0E+09	1.1E+09	2.7E+05
210		Pb	82	1.5E+04	3.7E+04	1.5E+00	3.7E+03	1.5E-01	2.0E+04	9.0E+03	2.5E+04	1.2E+00
211		Pb	82						4.0E+08	2.0E+07	5.0E+08	2.7E+03
212		Pb	82	7.4E+02	7.4E+06	2.2E+02	7.4E+05	2.2E+01	3.0E+06	1.0E+06	3.7E+06	1.4E+02
214		Pb	82						3.0E+08	3.0E+07	3.7E+08	4.1E+03
200		Bi	83						1.0E+09	3.0E+09	1.2E+09	4.1E+05
201		Bi	83						4.0E+08	1.0E+09	5.0E+08	1.4E+05
202		Bi	83						5.0E+08	1.0E+09	6.2E+08	1.4E+05
203		Bi	83						9.0E+07	2.0E+08	1.1E+08	2.7E+04
205		Bi	83						5.0E+07	9.0E+07	6.2E+07	1.2E+04
206	-	Bi	83	3.7E+04	1.5E+07	2.2E+03	1.5E+06	2.2E+02	2.0E+07	5.0E+07	2.5E+07	6.8E+03
207		Bi	83	7.4E+04	2.2E+07	2.2E+03	2.2E+06	2.2E+02	4.0E+07	6.0E+07	5.0E+07	8.2E+03
210	m	Bi	83						2.0E+06	2.0E+05	2.5E+06	2.7E+01
210		Bi	83	1.5E+03	1.5E+07	7.4E+01	1.5E+06	7.4E+00	3.0E+07	9.0E+06	3.7E+07	1.2E+03
212		Bi	83	3.7E+02	1.5E+08	1.1E+03	1.5E+07	1.1E+02	2.0E+08	9.0E+06	2.5E+08	1.2E+03
213		Bi	83						3.0E+08	1.0E+07	3.7E+08	1.4E+03
214		Bi	83						6.0E+08	3.0E+07	7.5E+08	4.1E+03
203		Po	84						9.0E+08	2.0E+09	1.1E+09	2.7E+05
205		Po	84						8.0E+08	1.0E+09	1.0E+09	1.4E+05
207		Po	84						3.0E+08	9.0E+08	3.7E+08	1.2E+05
210		Po	84	1.1E+03	2.6E+05	7.4E+00	2.6E+04	7.4E-01	1.0E+05	2.0E+04	1.2E+05	2.7E+00
207		At	85						2.0E+08	1.0E+08	2.5E+08	1.4E+04
211		At	85	7.4E+02	7.4E+05	7.4E+01	7.4E+04	7.4E+00	5.0E+06	3.0E+06	6.2E+06	4.1E+02
220		Rn	86			3.7E+03		3.7E+02				
222		Rn	86			3.7E+02		1.1E+02				
222		Fr	87						8.0E+07	2.0E+07	1.0E+08	2.7E+03
223		Fr	87						2.0E+07	3.0E+07	2.5E+07	4.1E+03
223		Ra	88	1.9E+03	2.6E+05	2.2E+01	2.6E+04	2.2E+00	2.0E+05	3.0E+04	2.5E+05	4.1E+00
224		Ra	88	2.2E+03	7.4E+05	7.4E+01	7.4E+04	7.4E+00	3.0E+05	6.0E+04	3.7E+05	8.2E+00
225		Ra	88						3.0E+05	2.0E+04	3.7E+05	2.7E+00
226		Ra	88	3.7E+03	3.7E+03	3.7E-01	1.1E+03	1.1E-01	7.0E+04	2.0E+04	8.7E+04	2.7E+00
227		Ra	88						6.0E+08	5.0E+08	7.5E+08	6.8E+04
228		Ra	88	2.2E+03	1.1E+04	7.4E-01	1.1E+03	7.4E-02	9.0E+04	4.0E+04	1.1E+05	5.5E+00
224		Ac	89						7.0E+07	1.0E+06	8.7E+07	1.4E+02
225		Ac	89						2.0E+06	1.0E+04	2.5E+06	1.4E+00
226		Ac	89						5.0E+06	1.0E+05	6.2E+06	1.4E+01
227		Ac	89	1.1E+03	7.4E+05	3.0E-02	7.4E+04	3.0E-03	7.0E+03	2.0E+01	8.7E+03	2.7E-03

1	2	3	4	5	6	7	8	9	10	11	12	13
228		Ac	89	1.5E+03	3.3E+07	1.1E+03	3.3E+06	1.1E+02	9.0E+07	4.0E+05	1.1E+08	5.5E+01
226		Th	90						2.0E+08	6.0E+06	2.5E+08	8.2E+02
227		Th	90	7.4E+02	7.4E+06	3.7E+00			5.0E+06	1.0E+04	6.2E+06	1.4E+00
228		Th	90	7.4E+02	2.6E+06	1.1E-01	2.6E+05	1.1E-02	2.0E+05	4.0E+02	2.5E+05	5.5E-02
229		Th	90						2.0E+04	3.0E+01	2.5E+04	4.1E-03
230		Th	90	1.9E+03	7.4E+05	3.0E-02	7.4E+04	3.0E-03	1.0E+05	2.0E+02	1.2E+05	2.7E-02
231		Th	90	1.1E+06	7.4E+07	1.9E+04	7.4E+06	1.9E+03	1.0E+08	2.0E+08	1.2E+08	2.7E+04
232		Th	90	1.5E+03	7.4E+05	2.6E-02	7.4E+04	3.7E-02	3.0E+04	4.0E+01	3.7E+04	5.5E-03
234		Th	90	1.5E+05	7.4E+06	7.4E+02	7.4E+05	7.4E+01	1.0E+07	7.0E+06	1.2E+07	9.6E+02
227		Pa	91						1.0E+08	4.0E+06	1.2E+08	5.5E+02
228		Pa	91						5.0E+07	5.0E+05	6.2E+07	6.8E+01
230		Pa	91	2.6E+03	7.4E+07	2.2E+01	7.4E+06	2.2E+00	2.0E+07	2.0E+05	2.5E+07	2.7E+01
231		Pa	91	7.4E+02	3.3E+05	1.5E-02	3.3E+04	1.5E-03	7.0E+03	6.0E+01	8.7E+03	8.2E-03
232		Pa	91						5.0E+07	8.0E+05	6.2E+07	1.1E+02
233		Pa	91	1.5E+06	3.7E+07	7.4E+03	3.7E+06	7.4E+02	5.0E+07	3.0E+07	6.2E+07	4.1E+03
234		Pa	91						9.0E+07	3.0E+08	1.1E+08	4.1E+04
230		U	92	3.7E+02	7.4E+05	3.7E+00	1.9E+05	3.7E-01	1.0E+05	2.0E+04	1.2E+05	2.7E+00
231		U	92						2.0E+08	3.0E+08	2.5E+08	4.1E+04
232		U	92	3.7E+02	3.0E+05	1.1E+00	1.1E+06	1.1E-01	8.0E+04	8.0E+03	1.0E+05	1.1E+00
233		U	92	1.9E+03	1.5E+06	7.4E+00	1.1E+06	7.4E-01	4.0E+05	4.0E+04	5.0E+05	5.5E+00
234		U	92	1.9E+03	1.5E+06	7.4E+00	1.1E+06	7.4E-01	4.0E+05	5.0E+04	5.0E+05	6.8E+00
235		U	92	1.1E+03	1.5E+06	7.4E+00	1.1E+06	7.4E-01	5.0E+05	5.0E+04	6.2E+05	6.8E+00
236		U	92	2.2E+03	1.9E+06	7.4E+00	1.1E+06	7.4E-01	5.0E+05	5.0E+04	6.2E+05	6.8E+00
237		U	92						6.0E+07	1.0E+08	7.5E+07	1.4E+04
238		U	92	1.9E+02	2.2E+05	1.1E+00	1.5E+06	1.1E-01	5.0E+05	5.0E+04	6.2E+05	6.8E+00
239		U	92						2.0E+09	7.0E+09	2.5E+09	9.6E+05
240		U	92				1.1E+06	3.0E+02	5.0E+07	1.0E+08	6.2E+07	1.4E+04
232		Np	93						1.0E+09	9.0E+07	1.2E+09	1.2E+04
233		Np	93						3.0E+10	1.0E+11	3.7E+10	1.4E+07
234		Np	93						8.0E+07	1.0E+08	1.0E+08	1.4E+04
235		Np	93						4.0E+08	5.0E+07	5.0E+08	6.8E+03
236	m	Np	93						2.0E+07	1.0E+06	2.5E+07	1.4E+02
236		Np	93						1.0E+04	1.0E+03	1.2E+04	1.4E-01
237		Np	93	2.2E+03	1.1E+06	3.7E-02	1.1E+05	3.7E-03	3.0E+03	2.0E+02	3.7E+03	2.7E-02
238		Np	93						3.0E+07	3.0E+06	3.7E+07	4.1E+02
239		Np	93	1.1E+06	3.7E+07	1.1E+04	3.7E+06	1.1E+03	6.0E+07	9.0E+07	7.5E+07	1.2E+04
240		Np	93						8.0E+08	3.0E+09	1.0E+09	4.1E+05
234		Pu	94						3.0E+08	8.0E+06	3.7E+08	1.1E+03
235		Pu	94						3.0E+10	1.0E+11	3.7E+10	1.4E+07
236		Pu	94						8.0E+05	7.0E+02	1.0E+06	9.6E-02
237		Pu	94						5.0E+08	1.0E+08	6.2E+08	1.4E+04
238		Pu	94	1.5E+03	1.9E+06	2.6E-02	1.9E+05	2.6E-03	3.0E+05	2.0E+02	3.7E+05	2.7E-02
239		Pu	94	1.5E+03	1.9E+06	2.2E-02	1.9E+05	2.2E-03	2.0E+05	2.0E+02	2.5E+05	2.7E-02
240		Pu	94	1.5E+03	1.9E+06	2.2E-02	1.9E+05	2.2E-03	2.0E+05	2.0E+02	2.5E+05	2.7E-02
241		Pu	94	3.3E+04	7.4E+07	1.1E+00	7.4E+06	1.1E-01	1.0E+07	1.0E+04	1.2E+07	1.4E+00
242		Pu	94	1.9E+03	1.9E+06	2.2E-02	1.9E+05	2.2E-03	3.0E+05	2.0E+02	3.7E+05	2.7E-02
243		Pu	94	2.6E+05	1.1E+08	2.2E+04	1.1E+07	2.2E+03	6.0E+08	1.0E+09	7.5E+08	1.4E+05
244		Pu	94	1.5E+03	1.5E+06	2.2E-02	1.5E+05	2.2E-03	3.0E+05	2.0E+02	3.7E+05	2.7E-02
245		Pu	94						8.0E+07	2.0E+08	1.0E+08	2.7E+04
237		Am	95						3.0E+09	1.0E+10	3.7E+09	1.4E+06
238		Am	95						1.0E+09	1.0E+08	1.2E+09	1.4E+04
239		Am	95						2.0E+08	5.0E+08	2.5E+08	6.8E+04
240		Am	95						8.0E+07	1.0E+08	1.0E+08	1.4E+04
241		Am	95	1.9E+03	1.5E+06	7.4E-02	1.5E+05	7.4E-03	5.0E+04	2.0E+02	6.2E+04	2.7E-02
242	m	Am	95	2.6E+03	1.5E+06	7.4E-02	1.5E+05	7.4E-03	5.0E+04	2.0E+02	6.2E+04	2.7E-02
242		Am	95	2.2E+03	3.7E+07	3.7E+02	3.7E+06	3.7E+01	2.0E+08	3.0E+06	2.5E+08	4.1E+02
243		Am	95	1.9E+03	1.5E+06	7.4E-02	1.5E+05	7.4E-03	5.0E+04	2.0E+02	6.2E+04	2.7E-02
244	m	Am	95						2.0E+09	1.0E+08	2.5E+09	1.4E+04
244		Am	95	7.4E+03	1.9E+09	3.7E+04	1.9E+08	3.7E+03	1.0E+08	6.0E+06	1.2E+08	8.2E+02

1	2	3	4	5	6	7	8	9	10	11	12	13
245		Am	95						1.0E+09	3.0E+09	1.2E+09	4.1E+05
246	m	Am	95						2.0E+09	6.0E+09	2.5E+09	8.2E+05
246		Am	95						1.0E+09	4.0E+09	1.2E+09	5.5E+05
238		Cm	96						6.0E+08	4.0E+07	7.5E+08	5.5E+03
240		Cm	96						4.0E+06	2.0E+04	5.0E+06	2.7E+00
241		Cm	96						5.0E+07	9.0E+05	6.2E+07	1.2E+02
242		Cm	96	1.9E+03	7.4E+06	1.9E+03	7.4E+05	1.5E-01	2.0E+06	1.0E+04	2.5E+06	1.4E+00
243		Cm	96	3.3E+03	1.9E+06	7.4E-02	1.9E+05	7.4E-03	7.0E+04	3.0E+02	8.7E+04	4.1E-02
244		Cm	96	3.7E+03	2.6E+06	1.1E-01	2.6E+05	1.1E-02	9.0E+04	4.0E+02	1.1E+05	5.5E-02
245		Cm	96	1.5E+03	1.5E+06	7.4E-02	1.5E+05	7.4E-03	5.0E+04	2.0E+02	6.2E+04	2.7E-02
246		Cm	96	1.9E+03	1.5E+06	7.4E-02	1.5E+05	7.4E-03	5.0E+04	2.0E+02	6.2E+04	2.7E-02
247		Cm	96	1.5E+03	1.5E+06	7.4E-02	1.5E+05	7.4E-03	5.0E+04	2.0E+02	6.2E+04	2.7E-02
248		Cm	96	1.9E+02	1.5E+05	7.4E-03	1.5E+04	7.4E-04	1.0E+04	5.0E+01	1.2E+04	6.8E-03
249		Cm	96	3.7E+04	7.4E+08	1.5E+05	7.4E+07	1.5E+04	2.0E+09	5.0E+08	2.5E+09	6.8E+04
245		Bk	97						8.0E+07	5.0E+07	1.0E+08	6.8E+03
246		Bk	97						1.0E+08	1.0E+08	1.2E+08	1.4E+04
247		Bk	97						4.0E+04	2.0E+02	5.0E+04	2.7E-02
249		Bk	97	2.6E+04	2.2E+08	3.7E+04	2.2E+07	1.1E+00	2.0E+07	8.0E+04	2.5E+07	1.1E+01
250		Bk	97	1.9E+03	7.4E+07	1.9E+03	7.4E+06	1.9E+02	4.0E+08	2.0E+07	5.0E+08	2.7E+03
244		Cf	98						9.0E+08	2.0E+07	1.1E+09	2.7E+03
246		Cf	98						1.0E+07	4.0E+05	1.2E+07	5.5E+01
248		Cf	98						8.0E+05	3.0E+03	1.0E+06	4.1E-01
249		Cf	98	1.5E+03	1.5E+06	1.9E-02	1.5E+05	1.9E-03	4.0E+04	2.0E+02	5.0E+04	2.7E-02
250		Cf	98	1.5E+03	3.7E+06	7.4E-02	3.7E+05	7.4E-03	1.0E+05	5.0E+02	1.2E+05	6.8E-02
251		Cf	98	1.5E+03	1.5E+06	2.2E-02	1.5E+05	2.2E-03	4.0E+04	2.0E+02	5.0E+04	2.7E-02
252		Cf	98	3.7E+02	2.6E+06	7.4E-02	7.4E+05	2.6E-02	2.0E+05	1.0E+03	2.5E+05	1.4E-01
253		Cf	98	1.5E+03	3.7E+07	1.1E+01	3.7E+06	1.1E+00	2.0E+07	7.0E+04	2.5E+07	9.6E+00
254		Cf	98	2.6E+01	3.7E+04	7.4E-02	3.7E+03	7.4E-03	1.0E+05	8.0E+02	1.2E+05	1.1E-01
250		Es	99						2.0E+09	2.0E+07	2.5E+09	2.7E+03
251		Es	99						3.0E+08	4.0E+07	3.7E+08	5.5E+03
253		Es	99	1.5E+03	7.4E+06	1.1E+01	7.4E+05	1.1E+00	8.0E+06	6.0E+04	1.0E+07	8.2E+00
254	m	Es	99	7.4E+02	7.4E+06	7.4E+01	7.4E+05	7.4E+00	1.0E+07	4.0E+05	1.2E+07	5.5E+01
254		Es	99	7.4E+02	3.7E+06	2.2E-01	3.7E+05	2.2E-02	8.0E+05	4.0E+03	1.0E+06	5.5E-01
255		Es	99	1.5E+03	1.1E+07	7.4E+00	1.1E+06	7.4E-01				
252		Fm	100						2.0E+07	5.0E+05	2.5E+07	6.8E+01
253		Fm	100						5.0E+07	4.0E+05	6.2E+07	5.5E+01
254		Fm	100	7.4E+02	3.7E+07	7.4E+02	3.7E+06	7.4E+01	1.0E+08	4.0E+06	1.2E+08	5.5E+02
255		Fm	100	1.5E+03	1.1E+07	2.2E+02	1.1E+06	2.2E+01	2.0E+07	8.0E+05	2.5E+07	1.1E+02
256		Fm	100	3.0E+01	3.3E+05	3.7E+01	3.3E+04	3.7E+00				
257		Fm	100						2.0E+06	9.0E+03	2.5E+06	1.2E+00
257		Md	101						3.0E+08	4.0E+06	3.7E+08	5.5E+02
258		Md	101						3.0E+06	1.0E+04	3.7E+06	1.4E+00

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