Recent Developments and Applications of Isotopic Neutron Sources[†]

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1. Introduction

As new applications for neutron sources developed there was a demand for different geometrical shapes and sizes, although of course a right cylinder was in general the preferred geometry. Sources were made ranging in form from long thin lines for neutron level gauging, to annular rings for back scatter applications. The form of the active material was also improved for some applications from powdered compacts which could be friable and release active powder if the source containment was breached, to a ceramic form which was inherently safer in accident situations. The development of sources during the 1960's has been reviewed^{1,2)}

During this period there was a growing number of applications, including a wide variety for process control. Activation analysis techniques developed for trace elements using reactor sources were now starting to be used for major element constituents using isotope sources. With increasing sophistication of electronics and detector systems two distinct trends have occurred, on the gauging front smaller source activities could be used for a given sensitivity, whilst in the activation analysis field larger source activities were demanded to realise the full potential and sensitivity of the technique. More recently the advent of Cf-252 has increased the source emissions readily available and as a result other applications such as neutron radiography are now possible. In the 1950's a neutron source emission of 10^8 n/s was regarded as exceptionally

high but today sources of 10^{10} n/s are used regularly and applications are being discussed which will require sources of 10^{12} n/s.

The growth of the nuclear power industry which is based on neutron reactions has naturally created a very large demand for measurement and control techniques based on these neutron reactions. Applications abound through the whole fuel cycle, prospecting and bore hole exploration, pit face and truckload analysing, chemical processing control, pellet and fuel rod assay and quality control, primary reactor start-ups, waste assay and disposal. The growth of the nuclear power industry has also coincided with and to some extent underlined the need for greater safety and control of the environment. In the manufacture of radioactive sources this concern has shown itself in much more stringent design procedures and source testing³⁾.

2. Radioisotope Neutron Sources

Radioisotope Neutron Sources are conveniently divided by the type of nuclear reaction taking place into three groups, (i) (γ, n) sources, (ii) (α, n) sources and (iii) spontaneous fission sources. Since the source developments which have taken place are very much interlinked with the source applications both aspects will be covered separately for each of the three

[†] アイソトープ中性子源の最近の進歩と利用。

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source groups.

2.1 Photo neutron sources

There are two basic forms of (γ, n) source, homogeneous and heterogeneous. In the homogeneous type equal volume mixtures of emitter and target are encapsulated usually in stainless steel and in the heterogeneous type, rods or cylinders of emitter are closely associated with rods or cylinders of target. The optimum arrangements for target and emitter are shown in Fig. 1.

Fig. 1 Neutron emission from homogeneous and heterogeneous photo-neutron sources showing optimum design.

Developments in photo neutron sources

The most frequently used (γ, n) sources employ antimony-124 with beryllium and the most common application of this type of high intensity source is for restarting power reactors after routine maintenance. Antimony-124 beryllium has a 60.9 day half-life which although not long is sufficient for a well planned reactor routine. The source tends to be rather bulky which is not too much of a problem in a power reactor but may not be acceptable for a marine reactor unit. A significant advantage for this system is that the sources can be produced inactively from natural antimony metal which is quickly activated once the reactor starts up.

A major problem with this type of source can be thermal stability, and the source designer has to take account of both the reactor operating temperature and nuclear heating within the source. Self-heating occurs as a result of elastic and inelastic neutron reactions and also due to the absorption of gamma rays in all the source materials. Inevitably the increased heating of modern reactors has led to source compatibility problems between the steel containment and the antimony metal^{4,5}.

Another problem is the swelling of the materials due to the production of gas in the crystal lattices and this also has become much more severe⁶⁻⁸.

The need to keep temperatures as low as possible has meant using production techniques which effectively remove any gas gaps between component parts, and for the outer containment at least this has meant heating before and during assembly, in effect shrinking the steel onto the beryllium. Because of the granular nature of antimony such a technique is not possible and so very careful selection of components is necessary to minimise gas gaps.

These techniques have worked well for reactors of the type LWR, and AGR, but the problems encountered with the HTRs and even more so with FBR's may have to be solved by the use of very small diameter sources perhaps encased in platinum pressure vessels.

The possibility of using oxides of antimony and beryllium to overcome the compatibility difficulties has been considered, but suffers from two disadvantages. The active volume increases significantly and the thermal conductivity decreases significantly. Also the stability of the oxides of antimony cannot be guaranteed. There are two oxides of antimony which can be considered, the trioxide (Sb_2O_3) which melts at 655°C and the tetroxide (Sb_2O_4) which decomposes at approximately 1,000°C, unfortunately unless the (Sb_2O_4) is very pure and free from (Sb_2O_3) some melting and corrosion will still take place.

Table 1 Properties of (α, n) beryllium neutron sources

Source	$T_{1/2}$	No. of α	Average α energy (MeV)	Practical emission ($n/s \cdot Ci$)	Weight of nuclide (mg/Ci)	γ Exposure (R/h $10^8 n/s$ at 1m)	Heat watts per $10^8 n/s$
^{242}Cm	163 d	1	6.1	3.0×10^6	0.30	<0.04	1.5
^{228}Th	1.91 y	5	6.4	2.0×10^7	1.2	3	1.0
^{244}Cm	18.1 y	1	5.8	2.5×10^6	12	<0.001	1.4
^{227}Ac	21.8 y	5	6.5	2.0×10^7	14	0.8	1.2
^{238}Pu	86.4 y	1	5.5	2.2×10^6	60	<0.001	1.4
^{241}Am	458 y	1	5.4	2.2×10^6	309	<0.1	1.4
^{226}Ra	1620 y	4	5.6	1.3×10^7	1000	6	1.2

Fig. 2 Large volume heterogeneous antimony beryllium source for an AGR reactor and smaller homogeneous source for a BWR reactor.

Two typical sources are shown in Fig. 2 one homogeneous and the other heterogeneous. Both are reactor restart sources one for an AGR the other for a BWR. In the larger heterogeneous source the antimony is completely encased in beryllium, in the smaller homogeneous source temperatures are kept low by using a small diameter.

2.2 Alpha- n neutron sources

The properties of the more common alpha emitting nuclides are given in Table 1.

With the exception of curium-244, sources containing all of these have been made at TRC. Only curium-242 is no longer made routinely. The nuclides divide sensibly into two groups americium-241 and plutonium-238 which each have a single alpha and low gamma dose rate, and radium-226, actinium

Neutron source emission data

Fig. 3 Neutron emission from Am-242(α, n) Be sources as the beryllium target is varied.

-227 and thorium-228 which have a chain of 4 or 5 alphas and high gamma dose rates. The heating in terms of watts per 10^8 neutrons is very similar in all cases but when, one considers the heating in terms of watts per cc or active volume then thorium-228 has to be considered with care.

The dependence of the neutron emission on target mass is shown in Fig. 3 for americium-241 and it can be clearly seen that ratios in excess of 10 : 1 do not significantly improve source emission. The specific neutron emission for an americium-241 beryllium neutron source is shown in Fig. 4. Clearly with no beryllium present the emis-

Fig. 4 Specific neutron emission for Am-241. Am-241 (α, n) Be neutron sources as the target mass varies. Also pressure developed after infinite time if all decay helium is released into available void.

sion of $\sim 1.5 \times 10^8 \text{ n/s} \cdot \text{Ci}$ is due to (α, n) reactions on the oxygen-18 contained in the americium oxide plus some fission while at the other extreme with no americium-241 present the emission is zero. The maximum emission occurs for a ratio of 0.67. Also in Fig. 4 is shown the pressure of helium which would be realised after infinite time due to alpha decay, assuming all the helium was released into the pellet and capsule void. From this curve we see pressures of the order of 2,000 psi being realised at target: alpha ratio of about 2 : 1. In practice we consider designs for maximum emission to have ratios of 5 : 1 for which the specific emission is approximately $2 \times 10^8 \text{ n/s/cc}$. The neutron spectra^{9,10}, we have for (α, n) sources are very complex and essentially are the result of neutron groups emitted from the various energy levels in the compound nucleus.

Development and applications for (α, n) sources

Most of the traditional applications for (α, n) neutron sources are still in use namely, reactor start-up, oil well logging, moisture gauges and major constituent activation analysis. Developments have been very largely

Fig. 5 Three unusual low emission (alpha, neutron) neutron sources showing different methods of source mounting.

Fig. 6 Two typical (alpha, neutron) sources for marine reactor start-up. The larger source contains 25 curies of Th-228/Be and 750mCi of Ra-226/Be. The smaller source contains 20 Ci of Ac-227/Be.

concerned with source manufacture and with increasing activities particularly for fast neutron activation but also for slow neutron activation. A selection of the more unusual low activity sources is shown in Fig. 5.

Sources for reactor start-up¹¹, have typical emissions of $5 \times 10^8 \text{ n/sec}$ and use in general tens of curies of thorium-228, actinium-227 or curium-242. Typical sources of this type are shown in Fig. 6 which are in fact for marine nuclear reactor. Usually such reactors are physically small and so the primary start-up source and secondary restart source are combined in a single rod. In the example shown the primary sources contained in one case 25 curies of thorium-228/Be and in the second case 20 curies of actinium-227/Be. In the first example the secondary source is generated from 1.5

grams of radium-226/Be which of course in the reactor flux becomes actinium-227/Be and thorium-228/Be, thus the necessary source flux is available throughout core life. In the second case the thorium-228/Be produced from the activation of the actinium-227/Be is sufficient for restart throughout core life. Recently for activation analysis there has been a trend to higher activity sources¹²⁻¹⁷⁾ and typical of this trend are the sources shown in Fig. 7. The annular source has an activity of 35 curies of plutonium 238-beryllium and is currently in use by Dr. T. B. Pierce of the Applied Chemistry Division at AERE Harwell who has been studying a whole range of industrial applications based on the following reactions¹²⁾.

Fig. 7 High activity (alpha, neutron) neutron sources.

Table 2 Reactions produced using a 35 curie Pu-238/Be neutron source

Element	Reaction	Product	
		E_{γ} (MeV)	$T_{1/2}$
Fluorine	$^{19}\text{F}(n, \alpha)^{16}\text{N}$	6.1	7.3 s
Aluminium	$^{27}\text{Al}(n, p)^{27}\text{Mg}$	0.84 1.01	9.5m
Silicon	$^{28}\text{Si}(n, p)^{28}\text{Al}$	1.78	2.3m
Phosphorus	$^{31}\text{P}(n, \alpha)^{28}\text{Al}$	1.78	2.3m
Iron	$^{56}\text{Fe}(n, p)^{56}\text{Mn}$	0.85 1.81	2.56 h
Titanium	$^{46}\text{Ti}(n, p)^{46}\text{Sc}$	0.14	18.7 s
Vanadium	$^{51}\text{V}(n, \gamma)^{52}\text{V}$	1.43	3.76m
	$^{51}\text{V}(n, p)^{51}\text{Ti}$	0.32	5.8m
Chromium	$^{52}\text{Cr}(n, p)^{52}\text{V}$	1.43	3.76m

A 25 curie¹⁷⁾ americium-241/Be source is currently being used for medical research application by J.A.R. McIntosh and G.R.D. Catto at the Department of Medicine in Aberdeen UK. The activation reaction $^{48}\text{Ca}(n, \gamma)^{49}\text{Ca}$ which produces a 3.1 MeV gamma ray with a half life of 8.7 minutes is being used to study the demineralising process associated with chronic renal failure. The calcium content of a hand is measured by neutron activation. Since the radiological features of renal bone diseases have been frequently observed first in the fingers, the calcium content of a hand when measured by neutron activation can give useful information.

An interesting industrial application which has been developed but which is not yet in use utilises a 44 curie americium-lithium neutron source. This was designed for use in a security system¹⁵⁾ in which traces of high thermal neutron cross-section elements such as gadolinium and samarium are applied to the articles of value and a flux of thermal neutrons constantly scans the entrance or detection zone. Prompt gammas from the gadolinium are detected by conventional counters and the sensitivity is such that 0.1 gram of gadolinium can easily be detected when to $20 \text{ n/cm}^2 \cdot \text{sec}$ at a distance of 2 ft from a 3×3 inch iodide crystal.

Sources for oil well logging have shown little change, the main problem here being the working pressure of 20,000 psi at a depth of 10 miles. Maraging steels are necessary to give the required capsule strength.

2.3 Spontaneous fission neutron sources

A number of heavy radionuclides decay by spontaneous fission but in most cases the yield of neutrons per gram of material is small. However for Cf-252 the neutron emission is $2.3 \times 10^{12} \text{ n/sec} \cdot \text{g}$ and with an effective half life of 2.65 yrs this is a very useful nuclide. Californium-252 decays 3.1 % by spontaneous fission emitting approximately four neutrons and two fission fragments in the process and 96.9% by alpha

decay to curium-248. The gamma dose rate of 160 mrad/h from one milligram at one metre is very low compared with that due to neutrons of 2,000mrem/h. Both neutron and gamma spectra are typical fission spectra with mean energies of 1.5 MeV gamma and 2.3 MeV neutron. The specific activity is fairly high, 536 curies per gram, but a really significant parameter is the very low alpha activity per neutron compared with other nuclides, Cf-252 4.3×10^9 n/sec·Ci, Th-228/Be 2×10^7 n/sec·Ci, Am-241/Be 2.2×10^6 n/sec·Ci. Thus approximately 2,000 times as much Am-241 activity is required compared with Cf-252 for the same neutron emission. Californium-252 is produced by irradiation of Pu-242, Am-243 or Cm-244 and since there are something like twelve transformations to make, very large fluxes $\sim 10^{16}$ n/cm²·sec are required for quantity production. The USAEC has suitable facilities and at present is the only supplier operating commercially. The very early optimistic predictions for the sales of Cf-252 have now become more realistic and a steady increase in the numbers of applications are now taking place, although so far there is no major application in which Cf-252 has proved to be unique.

Californium is supplied in two basic forms, as the oxide or as a cermet of californium oxide and palladium-terbium alloy which can be bought in the form of wire or pellets. We prefer to buy the oxide which gives us the maximum flexibility for source manufacture. Details of the techniques used in the UK have been reported¹⁹⁾ elsewhere, and to date over 300 sources have been made.

Other methods of source manufacture²⁰⁻²³⁾ which have been used include metallic cermets using palladium and gold, adsorption onto aluminium and alumina powder, fusion into silica spheres, electro deposition, vacuum deposition and self transfer deposition. Clearly the technology of the manufacture of sources ranging from 10^2 n/s to 10^{10} n/s is well developed and in general awaiting application. All of these tech-

Fig. 8 Range of Californium-252 neutron sources made for special applications. Emissions vary from 4×10^5 neutrons per second to 5×10^9 neutrons per second.

Table 3 Applications for Cf-252 in USA

On-stream process control	13 Undersea mineral
1 Uranium ore—pit face assay	Neutron irradiation
2 Uranium ore—truck assay	14 Industrial-Discrete sample analysis
3 Uranium mill—feed assay	15 Cement in soil
4 Portland cement—rawmix	16 Wet concrete analyser
5 Vanadium in oil	17 Classroom demonstration
6 Sulphur in coal	Neutron radiography
7 All other ores	18 R and D Camera
Neutron gauging	19 Field camera
8 Ordinance	Neutron multiplier
9 Moisture	20 Radiography
Mineral exploration	21 Activation analysis
10 Borehole uranium	Nuclear materials assay
11 Borehole mineral (activation)	22 Fuel rod scanner
12 Borehole lithology (n-thermalisation)	23 Bulk assay
	24 Pellet assay
	25 Reactor start-up

niques are used at Amersham. A range of californium sources for special applications are shown in Fig. 8.

Applications for Californium-252

A recent review²⁴⁾ of the potential market for devices using Cf-252 in USA has been made by P.H. Permar in which twenty five enduses in eight market segments are now recognised Table 3.

Our experience so far is that californium is well suited for reactor start-up, activation analysis where very large fluxes are required, nuclear material assay, and nuclear safeguards. Californium is also in regular use for moisture gauges and backscatter gauges where the half-life of 2.65 yrs is not regarded as too short but rather an advantage in the unlikely event of loss or accident. We have made a number of sources also for medical research and dosimetry measurements including one or two sources for after-loading systems. We have had enquiries for large sources for neutron radiography but so far the technique in Europe using such sources is not widely used.

Reactor start-up

The world's shortage of energy has inevitably led to a demand for larger reactors. These larger cores have usually required much thicker biological shielding which in turn has meant increasingly large distances between the neutron flux and the detectors outside the shield. Thus the emission required from a start-up source has been gradually increasing from typically 2×10^8 n/s to 10^{10} n/s which is used at present in 1,200 MW(e) reactors. Also the length of sources is increasing with core size typically from 2 meters to 4.5 meters. These changes have meant that californium has become the preferred isotope, because of its small active volume and low alpha activity. For 10^{10} n/s approximately 2 curies of Cf-252 which has an active volume of 10^{-3} ccs are required compared with 500 curies of thorium-228 which when mixed with beryllium occupies a volume of 10 ccs. We recently supplied reactor start-up sources which had an emission of 8×10^9 n/s. The sources consisted of two rod assemblies approximately 1 cm diameter 450 cms long, each rod containing ten active cells approximately 8 mm diameter $\times$ 12 mm long. Because these source rod assemblies were extremely flexible support was necessary during manufacture at all times and at the same time of course personnel has to be shielded from the very high dose

rates. Each reactor source is different but the procedure for this source serves to illustrate the problems. The inner cells were manufactured by micro-dispensing californium solution into vacuum melted stainless steel capsules which were argon arc welded.

These cells were decontaminated, tested for leakage of radioactive material and then each was further encapsulated in another capsule with was helium filled. This doubly encapsulated source was helium leak tested and the neutron emission accurately measured by using an array of BF₃ counters in a suitable moderator assembly. The outer source tube had one end plug welded in and radiographed, was fully helium leak tested and put inside a protective tube. The whole assembly was placed inside the transport container and the individual sources and spacers were loaded, the positions being carefully checked throughout. Using special jigs the assembly was filled with helium, the other end plug put in and argon arc welded. Helium leak tests and radiography were then carried out on the completed sources.

Table 4 Reactions produced using Cf-252 neutrons

Element	Reaction	Product	
		E_{γ} (MeV)	$T_{1/2}$
Aluminium	$^{27}\text{Al}(n, \gamma)^{28}\text{Al}$	1.78	2.3m
Sodium	$^{23}\text{Na}(n, \gamma)^{24}\text{Na}$	1.37 2.75	15 h
Magnesium	$^{26}\text{Mg}(n, \gamma)^{27}\text{Mg}$	0.84 1.01	9.5m
Silicon	$^{28}\text{Si}(n, p)^{28}\text{Al}$	1.78	2.3m
Phosphorus	$^{31}\text{P}(n, \alpha)^{28}\text{Al}$	1.78	2.3m
Chlorine	$^{37}\text{Cl}(n, \gamma)^{38}\text{Cl}$	1.6 2.2	37m
Potassium	$^{41}\text{K}(n, \gamma)^{42}\text{K}$	1.52	12 h
Calcium	$^{48}\text{Ca}(n, \gamma)^{49}\text{Ca}$	3.09	8.8m
Vanadium	$^{51}\text{V}(n, \gamma)^{52}\text{V}$	1.43	3.76m
Manganese	$^{55}\text{Mn}(n, \gamma)^{56}\text{Mn}$	0.85 1.81	2.56 h
Copper	$^{65}\text{Cu}(n, \gamma)^{66}\text{Cu}$	1.04	5.1m
Silver	$^{109}\text{Ag}(n, \gamma)^{110}\text{Ag}$	0.66	24 s

Activation analysis

Typical of activation analysis arrangements is the one which is used at AERE Harwell¹²⁾. A tank of water 2'6" in diameter $\times$ 8' deep is sunk into the laboratory floor. Eight sources each containing 12.5 μ g Cf-252 are distributed around the irradiator position into which samples are delivered by a pneumatic transfer system. Reactions produced in this facility are shown in Table 4.

Nuclear materials assay and safeguards

The whole range of application of neutron techniques for non-destructive measurements in safeguards has been discussed in the literature by D.R. Terrey²⁵⁾. The range of source requirements vary widely from 25 μ g to several milligrams Cf-252 some times used in conjunction with medium energy (<1 MeV) neutrons from americium-lithium sources at 10^6 n/s, for sub threshold measurements. Typical of this range is a source array used at ISPRA in Italy for the measurement of U-235 content of HTR fuel balls which consist of about 1g of highly enriched uranium and 10g of thorium as oxides dispersed in 200g of graphite. The balls selected for measurement are irradiated in a moderator assembly which has four 20 μ g Cf-252 sources as capsules 7.8mm diameter $\times$ 10mm long giving a thermal flux of 5×10^5 n/s $\cdot$ cm². After one minute the balls fall into a detector assembly of He-3 tubes in moderator where the delayed neutrons are counted. 1-2% reproducibility at the 95% confidence level is attained.

Many other techniques for the measurement of fissile and fertile material have been reported^{26)~29)}. Some of these are now commercially available with such names as IS AF, ISAS, VERPACS, VDC.

Medical applications

Cf-252 sources can be used for both diagnostic and therapeutic purposes. In the diagnostic area sources can be used for either partial body or whole body activation analysis and two 200 μ g sources in small

right cylinder capsules have been supplied to the team led by Dr. K. Boddy at the Scottish Research Reactor Centre at East Kilbride for research in this field³⁰⁾. Cf-252 is unlikely to be used as an alternative to accelerator or reactor beams for teletherapy but may be of clinical use for brachytherapy. Sources containing 500-600 μ g of Cf-252 suitable for use in after-loading equipment have been supplied for medical studies Fig. 9. Extensive work is being carried out with small sources largely under the auspices of USAEC, who are operating a loan programme whereby research hospitals can borrow clinical needlers and sources.

Fig. 9 500 microcuries Californium-252 sources used for medical research in after-loading equipment.

Neutron radiography

Neutron radiographic work using isotopic sources has been reported extensively in the USA^{31,32)} and some effort is being applied now in the UK. Sources of 500 μ g are being used but so far the potential in the aerospace industry for finding corrosion, stress cracking etc. has not been realised. In the UK radiography has been largely confined to reactor centres where large fluxes are available although some work has been done in the Universities^{33,34)}, using isotopic sources.

3. Radioisotope Neutron Source Design

As manufacturers of isotopic neutron sources we cannot over-emphasise the importance of source design. The range of uses and the environments to which sources are

exposed is very wide indeed ranging from the normal calibration source used in a measurement laboratory where no undue stresses are put on the source and the source is constantly in view, to the measurement of wear of the insulating lining walls of a steel blast furnace in which the source is subjected to very high temperatures in the strongly oxidising and at other times strongly alkaline conditions of molten slag.

A source design procedure must start from the expected operating conditions and then from considerations of half life, required emission, neutron energy volume etc. decide on the most suitable nuclide and the most suitable chemical form of that nuclide. The operating medium, pressure, temperature, neutron and gamma fluxes etc. would seem obvious design parameters and yet it is often difficult to get such data either because the source user does not know, or has not considered the problem or because the application may be very sensitive commercially. However, assuming that all the environmental parameters are available, then the source design can follow a fairly predictable path.

Design considerations

- 1) From the required emission, nuclide, and target material one can calculate the activity required and the active volume.
- 2) Gas evolution:- All radioactive neutron sources produce gas in one way or another, but generally the production can be considered in two ways.
 - a) Nuclear reactions such as alpha decay, $(n, 2n)$, (n, α) , fission, etc. producing such gases as helium, tritium, fission products, etc.
 - b) Chemical reactions or dissociation. Some sources contain salts, which in extreme situations could lead to corrosion or dissociation within the source.
- 3) Heating:- All radioactive neutron sources are subject to heating and this can be considered in two ways.
 - a) Internal heating from nuclear reaction both spontaneous and induced.

- b) External heating due to radiation, conduction, convection or chemical action.

- 4) Capsule Material. Most capsules are made from stainless steel, vacuum melted AISI 316L, but occasions arise when because of chemical compatibility, high temperature, very high pressure or the production of unwanted radiations within the capsule material other materials must be used.

Capsules are made from maraging steel, zircalloy, platinum, etc.

- 5) Design of the containment or capsule can now proceed having an awareness of many considerations some of which are summarised below.

- a) Pressure Vessel Codes such as DIN, BS 1500, ASME VIII, JIS, etc.

- b) Welding or sealing technique. The chosen method will determine the seal design. Also whether welds must have full penetration, minimum stress etc. will have a substantial impact on the capsule design.

- c) Active material stability. The optimum physical form of the active material is a function of all the parameters which operate on the capsule material, pressure, temperature, gas evolution, etc. and the stability and compatibility of the active material throughout source life must be assessed.

- d) Production methods. The source may be produced by wet or dry, chemical or physical techniques, also the source geometry may be a very important parameter.

- e) Quality Control. Techniques using ultrasonics, dye penetrants, radiography, helium leak tests, pressure tests, emission measurements, etc. sometimes have a considerable impact on capsule design.

- f) Radioactive Regulations and Codes of Practice. Sealed Sources Regulations, Special Form Tests, ANSI Tests, ISO Tests, all have to be considered. The requirement for a source to pass the appropriate tests is quite often the limit-

ing factor determining source life.

- g) Transportation. Air, Road, Sea all present different problems. Transport Containers may have to be designed and of course licensed through the appropriate authorities.

Clearly there is a wealth of experience and know-how required for this design process and the procedures outlined here are an indication of the ever growing awareness and importance of safety standards. There is much discussion at present concerning the safe working life of a source, the criteria which should apply and of course the method of policing and applying the necessary procedures. When the half-life of the radionuclide is measured in centuries clearly to control what happens to a source in future years is a matter of concern. In the long term this is clearly a problem for National or International Regulatory Bodies, but source manufacturers have some responsibility to ensure the integrity of the source throughout the working life which may be thirty years in the case of reactor start-up, or ten years in the case of an industrial gauge.

4. Summary

It is clear from this review that there are a number of applications which require high activity isotopic neutron sources and it seems likely that the expansion seen over the last decade or so will continue.

The nuclear power industry, particularly in this post oil-crisis era will flourish and with it the need for nuclear instrumentation and methods.

What has become clear is that the advent of Cf-252 has not replaced the conventional (α, n) and (γ, n) sources, but rather has complimented them and that there will be a continuing need for each type of source.

The current emphasis on source safety will put an increasing demand on the source manufacturer but by careful consideration of the various design parameters, adequate sources can be developed.

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