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A REVIEW OF CURRENT KNOWLEDGE OF THE TRANSFER OF RADIOSTRONTIUM TO MILK AND POSSIBLE COUNTERMEASURES

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EXECUTIVE SUMMARY

In this review we describe current information on the transfer of radiostrontium to milk, and critically evaluate available countermeasures to reduce radiostrontium contamination of milk.

Levels of radiostrontium in milk respond rapidly to those in the diet. The transfer of radiostrontium to milk is determined by calcium intake and status. Under normal ranges of dietary calcium intakes the transfer of radiostrontium to milk is likely to be inversely proportional to that of the dietary calcium intake. Therefore, the usefulness of conventional transfer coefficients for radiostrontium is limited, and predictions could be misleading. A relationship was noted between calcium intake and radiostrontium transfer to milk, which might allow improved estimation of radiostrontium transfer to milk.

The simplest and most effective countermeasure to reduce radiostrontium activity concentrations in milk is to provide dairy animals with uncontaminated feed, this has the added advantage of being effective for other radionuclides. If there is a limited supply of such feed preference should be given to dairy animals over animals reared for meat. If the affected area is very large or deposition occurs in late spring it will be difficult to supply uncontaminated fodder to large numbers of dairy cows and the use of alternative countermeasures needs to be considered.

The most practical, simple method of producing fodder or pasture grass with sufficiently low radiostrontium levels would be to apply lime to contaminated soils. The effectiveness of liming will depend on the prevailing calcium status of the soil; since most UK agricultural soils are not deficient in calcium the effect of liming may not be high. On organic soils liming may increase plant uptake of radiostrontium, and therefore the effect for major organic soil categories would need to be checked before application. The application of organic matter may also be effective, but the concomitant effect on radiocaesium needs consideration. Removing or diluting the top layer of contaminated soil, either by surface ploughing, or preferably skim and burial ploughing should also be considered, although the latter would not currently be possible since such ploughs are not available in the UK.

The use of additives given to ruminants to reduce radiostrontium in milk is an alternative countermeasure which should be considered, particularly if difficulties are encountered with supplying uncontaminated feedstuffs for dairy animals. Such countermeasures also have the advantage that they are rapidly effective, in contrast to many of the soil-based countermeasures. Furthermore, countermeasures based on additives are generally easy to administer to dairy animals, which are routinely handled twice daily, and potentially more cost-effective than soil-based treatments. Increasing the calcium intake by a factor of two should decrease radiostrontium levels in milk by a concomitant amount. However, relatively small increases in stable calcium intake are unlikely to achieve a substantial reduction. Other suggested additives to reduce the transfer of radiostrontium to milk are either of limited effectiveness (e.g. clay minerals) or need further investigation (e.g. calcium alginate) before they could be considered as a practically feasible alternative to calcium.

The effectiveness of available countermeasures varies. Radiostrontium activity concentrations decline rapidly in milk when feeding uncontaminated feed, and the rates of loss are determined by the biological half-life of radiostrontium in ruminant milk. Soil treatment can give maximum reduction of ten fold, but

a factor of two or three is more common. Feeding dairy cows enhanced levels of Ca will give maximum reduction factors of two to three. Potentially higher reduction factors could be achieved if selective, and appropriate Sr binders were available. A summary of potentially effective countermeasure options which could be adopted is given below.

1 INTRODUCTION

Radiostrontium can be released into the environment during routine emissions from nuclear facilities, nuclear detonations or as a result of nuclear accidents. Generally, the transfer of two strontium isotopes to milk need to be considered: ^{89}Sr, with a physical half-life of 50.5 d and ^{90}Sr with a physical half-life of 28.5 y. Although ^{89}Sr has a shorter physical half-life the ingestion of both radiostrontium isotopes in milk is a potentially important route of exposure to humans, particularly infants. The amount of radiostrontium released following a nuclear accident and subsequently transferred to milk, will be one of the critical parameters in determining the need for actions to protect the population.

In this report, currently available information has been reviewed on the transfer of radiostrontium to milk. Information from a variety of sources has been considered. The source material includes (i) published information from the former Soviet Union arising from studies on the behaviour of radiostrontium after the Kyshtym accident, (ii) environmental and metabolic studies associated with the ^{90}Sr released by above-ground nuclear weapons tests, (iii) post-Chernobyl studies, on the behaviour of the deposit and information arising from fundamental research conducted over the last 9 years, and (iv) recent literature reviews on transfer, such as Coughtrey (1990), IAEA Handbooks (1994a; 1994b) and the REACT proceedings (Howard & Desmet 1993) in particular the REACT paper of Voigt (1993).

An objective of this study is to review the effectiveness of currently available countermeasures to reduce radiostrontium contamination of milk. The applicability of the countermeasure is considered with regard to the UK farming situation. Countermeasures directed at reducing radiostrontium transfer to plants have been effectively reviewed recently, and the conclusions from these reviews are presented here. For animal-based countermeasures the data has been less comprehensively reviewed. Additional literature, not previously considered, and new information from recent studies have been incorporated in the assessment.

2. RADIOSTRONTIUM METABOLISM AND TRANSFER TO ANIMAL PRODUCTS

There are stable isotopes of strontium present within the environment and typical concentrations in plant material of 26 mg kg^{-1} (dry matter) are quoted by Bowen (1966). There is some evidence that strontium may be an essential trace element to mammals (Rygh 1949) although this has not been confirmed. The metabolism of strontium cannot be discussed in isolation from that of calcium which is the most abundant mineral element in the body. Strontium follows the same metabolic pathways as calcium although there is differentiation between the two alkaline earth elements in many transfer processes (Comar et al. 1956; Lengemann 1963; Russell 1966).

Before considering the transfer of radiostrontium to animals and their products we will briefly discuss the calcium requirements and metabolism of ruminant livestock. The main emphasis of this section is placed on dairy animals, especially cattle.

2.1 CALCIUM REQUIREMENTS AND METABOLISM

The plasma concentration of calcium is homeostatically controlled by a number of regulatory mechanisms. These include the parathyroid gland, which responds to small decreases in plasma calcium by stimulating calcium mobilization of skeletal reserves, renal control of urinary calcium excretion, the resorptive capacity of bones and the role of vitamin D in calcium absorption from the intestine and resorption from bone (Draper 1963).

2.1.1 The calcium content of ruminants and their products

The skeleton contains 99% of the total body calcium with concentrations in ruminant bone varying between 110 and 200 g Ca kg^{-1}(ARC 1980). The calcium content of other tissues is low: fat contains virtually no calcium and soft tissues approximately 0.1 g Ca kg^{-1} fw. For dairy cattle a representative value for the calcium content of animals of 14 g Ca kg^{-1} empty body weight has been recommended (ARC 1980). However, body calcium is lost during both late pregnancy and especially lactation (Braithwaite et al. 1970). Skeletal reserves of calcium will keep the calcium content in milk constant when absorbed calcium cannot meet the animals requirements for milk production. Withdrawal of calcium from bone occurs at varying rates from different parts of the skeleton (Underwood 1981). The trabecular bones (ribs, vertebrae, sternum and ends of the long bones) are the first reserves to be used and the cortical bone (compact shafts of the long bones such as femur and tibia) are used last.

There is a high concentration of strontium in milk compared to that in blood (Twardock 1963), and the calcium concentration in the milk of some species can exceed that in the blood by 30 fold (Shennan 1990). This indicates that there must be an active transport mechanism for calcium from the plasma across the mammary gland into milk. The recommended representative value of the calcium content in sheeps milk is 1.6 g kg^{-1} (ARC 1980) and a value of 1.0-1.8 was suggested to be typical for goat milk by Comar (1966a). More recent data give calcium contents for whole cow milk (breed unspecified) of 1.15 g kg^{-1} (National Dairy Council 1992); values of 1.1, 1.02 and 1.62-2.59 g kg^{-1} are given as typical values for cow, goat and sheep milk respectively by the British Sheep Dairying Association (pers comm.).

For cattle, there are correlations between the calcium and both the fat and protein content of milk (ARC 1980). The positive relationship suggested between calcium and fat contents is that of Ellenberg et al. (1950):

$$Ca = 0.79 + 0.011F$$

where Ca = calcium concentration (g kg^{-1})

F = fat content (g kg^{-1})

On the basis of the limited data presented by ARC (1980) the relationship also appears to be valid for sheeps milk.

2.1.2 Calcium absorption and excretion

Calcium absorption decreases with age, and is approximately 100 % in animals which are a few weeks old (Bronner 1964). The extent of calcium absorption in the adult ruminant gut is governed by the animals calcium requirement and occurs by both passive and active (initiated by vitamin-D) transport mechanisms. There is no relationship between calcium absorption and its dietary intake under normal conditions of calcium supply (Bronner 1964; ARC 1980). It has been suggested that, at a given intake rate, absorption of dietary calcium depends upon the net requirements of the animals and at a given net requirement, the true absorption coefficient of calcium varies inversely with feed calcium (Comar et al. 1966a; ARC 1980). Absorption of dietary calcium has been shown to increase in the presence of lactose and some carbohydrates (Dupuis & Fournier 1963).

The endogenous faecal excretion of calcium has generally been considered to be independent of the amount of calcium ingested or absorbed (Visek et al. 1953; ARC 1980), and directly proportional to live weight. The ARC (1980) give a mean value for endogenous faecal excretion of of 15.7±3.8 mg kg^{-1} live weight d^{-1} for cows and a similar value of 16.3±0.5 mg kg^{-1} live weight d^{-1} for sheep. However, in a more recent publication Braithwaite (1982) has shown that the endogenous faecal loss of calcium varies according to feed intake (endogenous faecal losses increasing by about 0.64 mg/d/kg body weight for each 1g/day/kg body weight increase in food intake). Urinary excretion is comparatively unimportant at less than 1 mg kg^{-1} live weight d^{-1}.

2.1.3 Calcium requirements

In order to meet calcium requirements the diet must contain sufficient available calcium; usually 45-70% of dietary calcium is in an available form for absorption by ruminants (ARC 1980; Underwood 1981). Recommended values for the daily calcium requirements of lactating cattle are given in Table 2.1. Generally, it is unlikely that dairy animals within the UK will be receiving a diet with calcium levels below those required (Underwood 1981). However, some lactating animals, especially in early lactation, cannot absorb adequate amounts of ingested calcium to meet their requirements. These animals will therefore be in negative calcium balance and there will be resultant losses of calcium from the skeleton. Calcium intake has been shown to affect bone remobilization: cows receiving 90 g $d^{-1}$of Ca about 50% of the milk calcium comes from the skeleton, whereas at 281 g Ca d^{-1} only 2% came from the bone (Comar & Wasserman 1964).

Table 2.1 Dietary requirements (g d^{-1}) of calcium by lactating cows (ARC 1980).

Breed	Milk yield (kg d^{-1})			
	10	20	30	40
Jersey	30	50	71	92
Ayrshire	29	46	63	80
Friesian	31	48	64	81

NB. values assume 68 % of dietary calcium will be in a form available for absorption.

Calcium requirements for lactating ewes have been estimated to be 4.3 g d^{-1} for a 50 kg ewe to 5.1 g d^{-1} for an 80 kg ewe (ARC 1980). Maintainance values for goats range from 2 g Ca d^{-1} for 40 kg animals to 4 g Ca d^{-1} for 80 kg animals (Wilkinson & Stark 1987). For lactating nannies an additional 2-3 g Ca kg^{-1} milk will be required depending upon the milks' fat content.

It has been suggested that the values recommended by ARC need some modification to take into account variable losses in endogenous faecal calcium (Braithwaite 1982) and that no allowance is given during mid to late lactation for the replacement of skeletal reserves lost during late pregnancy and peak lactation (Braithwaite 1983). Recommended values derived more recently by the Agricultural University of Denmark, are considerably higher than those in Table 2.1 (Østergaard & Neimann-Sørensen 1983). In the Danish publication, maintenance values for cattle are approximately 2.4 times higher and values suggested to meet milk requirements are about 1.2-1.4 times higher than those recommended by ARC. The higher values, which aim to ensure that Ca intake is in excess of minimum requirements, take into account increased estimates for endogenous faecal excretion and potential differences in availability of dietary calcium (Hansen pers. comm.).

2.1.4 Dietary calcium:phosphorus ratio

Calcium and phosphorus are essential elements, as the principle components of the skeleton, and for a number of biochemical processes. Calcium, for instance, is required for blood clotting, nervous control, muscle contraction/relaxation and for controlling metabolic rate. Phosphorus is a component of nucleic acids, required for cell growth and differentiation; it helps maintain osmotic and acid-base balance and is involved in a number of metabolic functions (energy utilisation and transfer, phospholipid formation and fatty acid transfer). The control of the two elements is linked and deficiency in either element leads to the release of calcium phosphate from bone. The Ca:P ratio in the diet is therefore important with a range of 1:1 to 2:1 recommended for ruminants (ARC 1980). Grains have especially low Ca:P ratios (c. 0.15) and legumes especially high values (c. 5) (Mackenzie 1980). Typical values for grass and grass hay/silage are in the range 1.6-2.3.

2.2 RADIOSTRONTIUM METABOLISM IN RUMINANTS

Within normal levels of strontium intake, the metabolism of strontium is regulated by the calcium level (Comar 1967; Lengemann et al. 1974). Goldman et al. (1965) reported that radiostrontium uptake in sheep and deer was roughly inversely proportional to the dietary calcium level. A similar suggestion was made by Comar et al. (1966a) concerning the transfer of calcium to milk. Factors which are known to effect calcium metabolism (eg. vitamin-D, carbohydrates, protein level and dietary phosporus) have been shown to similarily influence strontium absorption and transfer to milk (Comar et al. 1961; Comar et al. 1966a; Lengeman et al. 1974).

Strontium is not concentrated in any tissue other than bone (Coughtrey & Thorne 1983). Muscle has been reported to have lower levels than other soft tissue (Coughtrey & Thorne 1983) whilst fat has the lowest levels within the body (Annenkov et al. 1973). Approximately 98% of body radiostrontium is present in bone after periods of prolonged ingestion (Coughtrey 1990).

Typical values for the excretion of intravenously administered radiostrontium in ruminants range between 4 and 20 % (Comar & Wasserman 1964) For instance, Garner et al. (1960) found that over eight days following a single intravenous injection of radiostrontium the total endogenous faecal, urinary and milk excretions by cows were 18 %, 2% and 16% of the administered activity respectively.

A value for the gastrointestinal absorption of radiostrontium of 0.2 for adult animals has been recommended by Coughtrey and Thorne (1983). However, given the discrimination reported between strontium and calcium during absorption of 0.25 - 0.3 (see section 2.2.2) a strontium absorption value of 0.2 would suggest a rather high value for calcium absorption. The accuracy of any recommended value of strontium absorption when applied to a specific situation will be influenced by the calcium requirements and supply of the animals.

2.2.1 The transfer of radiostrontium to milk

The level of radiostrontium in milk responds rapidly to that in the diet and a pseudo-equilibrium in milk concentrations is rapidly reached when animals are introduced to a contaminated diet. After single administrations of radiostrontium Comar & Wasserman (1964) noted that the peak activity concentration in the milk of cattle occurred after 2 days, and constituted 0.02 % of the administered activity per litre of milk. For chronic administration plateau levels were reached in goats and cows at 3 and 4-6 days respectively after begining to administer dietary radiostrontium (Comar et al. 1961). Variation in the total recovery of radiostrontium in milk has been shown to be related to milk yield (Garner & Sansom 1959; Comar & Wasserman 1964).

Transfer of radiostrontium to milk has been shown to be reduced by high levels of dietary Ca and increased by low dietary Ca levels (Comar et al. 1961; Comar et al. 1966a; Annenkov et al. 1973; Korneev et al. 1973). Within normal dietary limits of Ca the radiostrontium transfer to milk was inversely proportional to the dietary Ca (Comar & Wasserman 1964).

Comar et al. (1961) suggested that the level of calcium in dietary feedstuffs may have an influence on the transfer of radiostrontium and the efficiency of administering stable calcium to reduce milk radiostrontium levels. There is some evidence within the literature to show that the transfer of radiostrontium to milk varies with diet composition. For instance, sheep and deer fed a cereal-based pelleted diet retained approximately twice the amount of radiostrontium and calcium in bone as those fed on alfalfa (Goldman et al. 1965). The authors suggested that the comparatively high levels of calcium and a high ratio of Ca:P in alfalfa may have caused the lower strontium transfer from this diet. In a review, Garner (1971) reports unexplained differences between the transfer of radiostrontium to the milk of cattle on different diets from a number of studies. However, given that transfers were found to be lower for animals on an alfalfa hay diet compared to animals grazing pastures it is possible that the suggestion of Goldman et al. (1965) could also explain the differences reported by Garner (1971). Buldakov et al (1964) and Buldakov & Moskalyev (1968) also report differences in the transfer of radiostrontium to milk on different diets which they related to the calcium content of the diet (Table 2.2).

Table 2.2 The transfer of ^{90}Sr to milk of cows receiving different diets (after Buldakov & Moskalev 1968).

Feed	Calcium intake in feed (g d^{-1})	F_m (d l^{-1})*
Oats	31-38	0.0020
Fresh vetch (a small legume)	66	0.0012
Fresh alfalfa	214-224	0.0006

*See section 2.2.1.ii for definition of F_m (transfer coefficient of radiostrontium from the diet to milk).

i) Half-lives of radiostrontium loss in milk

Sirotkin et al. (1969) found a four compartment-model best described the loss of radiostrontium from milk. They suggested half-lives of 0.5, 3, 16 and 315 days with respective fractions of excretion of 0.93, 0.06, 0.004 and 0.0006. Three components of loss were found by Kahn et al. (1965) giving $T_{1/2}$ values for radiostrontium in cow's milk of 0.77, 4.6 and >50 days. More recently, a biological half-life for ^{90}Sr in cow's milk of 3.5 d was estimated by Fabbri et al. (1994). The differences between these findings are likely to be due to differences in experimental procedure (ie. frequency of milking) and duration. However, it is clear that there will be a rapid decline in the radiostrontium levels in milk following the cessation of contamination. Differences in the importance of the long-term component of loss can be expected due to variation in the retention of radiostrontium in bone, which amongst other factors will depend upon the length of exposure to a contaminated diet and the Ca status of the animal.

ii) Transfer coefficients

The transfer of a radionuclide from the diet to milk is often expressed as the transfer coefficient (F_m), defined as the equilibrium ratio between the radionuclide activity concentration in milk and the daily intake of the radionuclide (Ward & Johnson 1986). Recently, available transfer coefficients for radiostrontium have been reviewed by Coughtrey (1990) and the International Atomic Energy Agency (IAEA) (1994b). The IAEA recommended that the value estimated after 100 d feeding of radiostrontium calculated by Coughtrey (1990) be used. Table 2.3 presents the values estimated by Coughtrey and the expected ranges in those values suggested by the IAEA.

Table 2.3 Recommended values for the F_m for radiostrontium to milk

Animal	F_m (d l^{-1}) Predicted value at 100d^{+}	Expected range^{++}
Cow	0.0028	0.001-0.003
Goat	0.028	0.006-0.039
Sheep	0.056	0.04^{+}*

$^{+}$(Coughtrey 1990)

$^{++}$(IAEA 1994b)

*Single value cited by Coughtrey

The transfer coefficient of radiostrontium to cows milk is considerably lower than that of goats and sheep. Only one value of F_m for sheeps milk was cited in the reviews. In a Soviet review, Annenkov et al. (1973) also present values for sheep after regular intake of between 0.0095 and 0.063 d l^{-1}; values for goats presented by these authors are 0.0061-0.013 d l^{-1}. Ca intake for these animals was not given.

Although the above values of F_m have been recommended for use in the estimation of radiostrontium levels in milk these values will vary with calcium status. Values of radiostrontium F_m for an animal, under conditions of normal calcium intake, are likely to be inversely proportional to the dietary calcium intake. A detailed analysis of the relationship between calcium intake and F_m has been carried out and the results are shown in Fig 2.1. The data are largely derived from experiments in Russia following the Kysthym accident, and in America and Europe during the era of above-ground weapons fallout era. It is evident that there is a relationship between the two parameters which could be used to select an appropriate F_m value in different circumstances. The Ca intake (x variable) was transformed using reciprocals and the F_m was regressed onto it to produce the fitted line:

$$F_m = 0.1046/\text{Ca intake} - 0.0028$$

$r^2 = 0.91$ F ratio = 295.49 with 29df

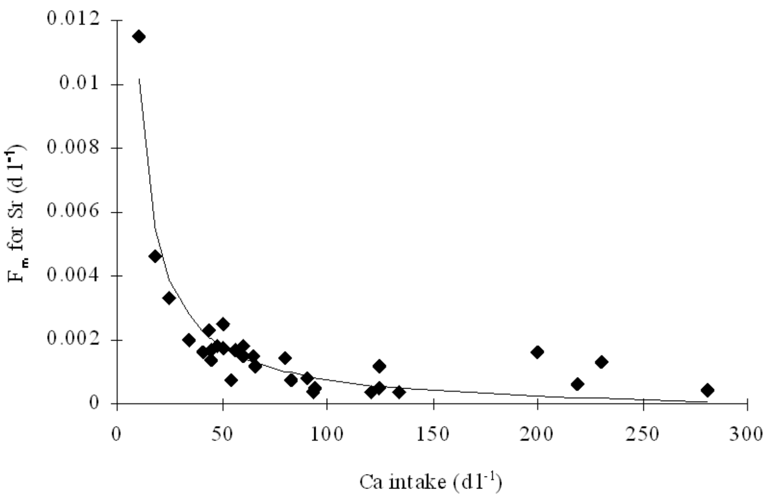

Figure 2.1 Relationship between the transfer coefficent for cow milk and the daily calcium intake.

Further analysis of the data, in particular to consider the relationship with regard to the Ca requirement of animals, will be carried out by the EC animal group (Howard et al. 1994).

The use of transfer coefficients to describe the transfer of radiostrontium to milk in the absence of any consideration of the calcium content of an animals diet was recognised as being of limited value during research in the 1950-60's (Garner 1971). This lead to the recommendation of the observed ratio approach discussed below.

2.2.2 Discrimination between strontium and calcium

It has long been recognised that there is a discrimination in the transfer of calcium and strontium across biological membranes (Comar et al. 1956; Lengemann 1963; Russell 1966). In animals, discrimination was observed for transfer across the gut and mammary gland, and for the rate of deposition to bone and urinary excretion (Lengemann 1963; Comar & Wasserman 1964). This led Comar et al. (1956) to suggest the use of the *strontium calcium observed ratio* (OR) to describe the overall discriminatory transfer between the diet and different body compartments or within the body. The observed ratio was often used to describe the transfer of weapons fallout radiostrontium to milk, where:

$$OR_{milk\text{-}diet} = \frac{\text{Sr/Ca in milk}}{\text{Sr/Ca in diet}}$$

Measurement of the OR ratio showed preferential transfer of calcium relative to strontium from the diet to milk (eg. Russell 1966; Annenkov et al. 1973; Lengemann et al. 1974). Values of $OR_{milk\text{-}diet}$ measured for weapons fallout radiostrontium in dairy cattle herds in a number of European countries have been collated by van den Hoek (1989) and for the United States by Comar (1966b). These values, together with additional data are presented in Table 2.4. The $OR_{milk\text{-}diet}$ value recommended by the United Nations (1962) was 0.11. Values of $OR_{milk\text{-}diet}$ for goats were in the range 0.09-0.22 and similar to those presented for cattle in Table 2.4 (Comar 1966b; Comar et al. 1966a; Lengeman et al. 1974). Indeed, reported $OR_{milk\text{-}diet}$ values are similar for all species including non-ruminants under normal dietary Ca intake regimes (Comar 1966b).

The $OR_{milk\text{-}diet}$ has previously been thought to be independent of the dietary calcium level (Comar et al. 1961; Comar et al. 1966a), although it was acknowledged that the $OR_{milk\text{-}diet}$ will be influenced by the proportions of milk strontium and calcium which are originating from skeletal reserves compared to the diet. For instance, the high value quoted by Sumerling

(1984) was for cows fed winter fodder with a comparatively low levels of ^{90}Sr compared with summer grazing, and since Ca levels in milk remained constant the author suggested that it may have been due to remobilization of ^{90}Sr from bone.

Table 2.4 $OR_{milk\text{-}diet}$ values measured for dairy cattle (mean (range)).

Country	Date	$OR_{milk\text{-}diet}$	Reference
Finland	1952	0.048 (0.033-0.075	Lakenen & Salo 1964
	1961-1962	0.047 (0.021-0.079)	Lakenen & Salo 1964
Belgium	1959	0.030 (0.022-0.036)	van den Hoek 1989
	1960	0.039 (0.023-0.054)	van den Hoek 1989
	1961	0.053 (0.049-0.056)	van den Hoek 1989
	1962	0.034 (0.029-0.042)	van den Hoek 1989
United Kingdom	1957	0.10 (0.07-0.16)	Cox et al. 1960
	1957	0.11 - stable strontium	Cox et al. 1960
	1981-83	0.1 - 0.4	Sumerling 1984
Germany	1960 May-July	0.11 (0.05-0.22)	van den Hoek 1989
	1960 Aug-Oct	0.08 (0.04-0.15)	van den Hoek 1989
United States			
Illinois		0.16	Comar 1966b
California		0.13	Comar 1966b
Minnesota		0.15	Comar 1966b
USSR			
Kyshtym		0.09 - 0.25	Annenkov 1964a
Kyshtym		0.06 - 0.29	Annenkov et al.1973

The collation above shows some comparatively high OR values which, for the USSR data, are associated with comparatively high Ca intakes of 120 - 240 g Ca d^{-1}. The low value in Table 2.4 found in Finland was thought to be due to high stable strontium levels (Lakanen & Salo 1964). However, this would seem unlikely, assuming the animals were receiving an adequate calcium supply, since stable strontium values were only 2.7 times higher than those measured in milk samples from Germany, and stable strontium generally has little effect on radiostrontium transfer to milk (see section 3.3.4 ii).

An observed ratio for a transfer process is the result of a number of discrimination factors (DF's) (Comar et al. 1956), which for milk can be expressed as follows:

$OR_{milk\text{-}diet} = (DF_{absorption})(DF_{bone})(DF_{urine})(DF_{endogenous\ excretion})(DF_{milk})$ .... (DF_n)

The most significant discrimination in the transfer to milk occurs at the absorption stage ($DF_{absorption}$ = 0.25-0.30) (Lengemann et al. 1974). Uptake by bone discriminates in favour of calcium (Lengemann 1963) whilst strontium is preferentially lost from bone (Comar & Wasserman 1964). There is little discrimination between the two elements in endogenous excretion to the gut (Lengemann 1963; Annenkov et al. 1973; Lengemann et al. 1974). Discrimination by the kidney favours strontium excretion to urine (Comar 1966b). Twardock and Comar (1961) found a preferential excretion of calcium to milk ($OR_{milk\text{-}plasma}$=0.39) but in goats which were administered radiocalcium and radiostrontium into the mammary gland movement into the blood stream was non-discriminatory. Within milk proportionally more strontium than calcium is found to be bound to caesin (Comar & Wasserman 1964). Some typical OR and DF values for ruminants are collated in Table 2.5.

Table 2.5 Some typical DF and OR values for ruminant livestock (adapted from Lengeman (1963), Twardock (1963), Comar & Wasserman (1964), Lengeman et al. (1974)).

OR value	Cow	Goat	Sheep
$OR_{milk\text{-}diet}$	0.10	0.12	
$OR_{plasma\text{-}diet}$	0.17	0.28	
$OR_{milk\text{-}plasma}$	0.52-0.80	0.36-0.48	
$DF_{absorption}$	0.20-0.30	0.25-0.34	0.20-0.40
$DF_{urinary}$	0.7	0.6-0.7	0.6
$DF_{lactational\ milk}$	0.7	0.4	
$DF_{lactational\ body}$	1.3	1.1	

2.3 AGGREGATED TRANSFER PARAMETERS

By considering the transfer to milk of radiostrontium in terms of the ratio of the activity concentration in milk to the deposit per metre square the ecological charateristics of an ecosystem are aggregated and there is no requirement to estimate parameters such as herbage and hence radiostronitum intake. In the initial period after a deposition event the activity per unit area is likely to be amongst the first measurements available. Methods of relating radiostrontium activity concentrations in milk to the radiostrontium deposit are obviously useful. This measure of transfer is usually described as the aggregated transfer coefficient (T_{ag}) (Howard et al. 1991), where:

$$T_{ag} = \frac{\text{radiostrontium activity concentration in milk (Bq/l)}}{\text{radiostrontium deposit (Bq m}^{-2}\text{)}}$$

Most data to enable the estimation of T_{ag}'s are available from studies conducted within the CIS following the Kyshtym and Chernobyl accidents (Nikipelov et al. 1989; Prister 1990; Averin 1994; Shutov et al. 1993) (Table 2.8). In the Ukrainian Polesye the lowest T_{ag} values were obtained from areas with leached chernozem soils and the highest from soddy-podzolics and sand loams. Data are also available from a pasture (with a soddy podzolic/sandy loam soil) located 3.5 km WSW of the Chernobyl plant which were obtained during a study conducted in the summer of 1993 (Howard et al. 1993). The study pasture received some deposition associated with fuel particles.

Few T_{ag} values for radiostrontium are available prior to the Chernobyl accident. Values have been estimated from data presented for pastures artificially contaminated with ^{85}Sr (van den Hoek & Kirchman 1968, van den Hoek et al. 1969) (Table 2.6). Measurements were made over days 5 to eleven after ^{85}Sr was applied to different pasture types (permanent pasture, reseeded pasture and rotationally grazed pasture) by a crop sprayer. Measurements were made in both early summer and late summer/early autumn. The data presented in the Table is a mean of the two sampling times as no seasonal effect was observed. No effect of pasture type was observed although the milk from animals grazing under a rotational system was significantly higher than that from those freely grazing.

Values of T_{ag} for the UK following a single contamination event were predicted by Garner (1960). Under conditions which were intended to represent the worst case for British agriculture a T_{ag} value for 21 days after deposition of 0.031 was estimated. For comparison, MAFF conservatively estimate that the maximum permitted limit (MPL) for ^{90}Sr in milk of 125 Bq l^{-1}, would be exceeded in the event of ^{90}Sr deposition exceeding 3,910 Bq m^{-2}, based on the SPADE model. This is equivalent to a T_{ag} value of 0.032.

Prister (1990) reports that T_{ag} values measured in the Kiev region between 1987 and 1989 were similar to those measured in the Southern Urals for ^{90}Sr originating from the Kystymn accident. However, it is unclear over what period the Southern Urals measurements were recorded.

The concept of using T_{ag}'s to predict the transfer of radiostrontium to milk in the event of deposition of fallout needs further consideration. The values shown above vary considerably and values specific for different soil types and management regimes would need to be determined. Observed values for T_{ag} reported from the CIS have been divided into different pH categories to allow for the observed differences with soil type, with higher T_{ag} values given for soils with comparatively low pH (Prister 1990). Obviously the T_{ag} value for a given site will change with time after deposition; as it is dependent upon the ecological half-life of radiostrontium in milk at that site. Currently it would not be possible to advise that T_{ag} values be used to predict the transfer of radiostrontium from a deposit to milk in the UK.

Table 2.6 T_{ag} values determined for the transfer of radiostrontium to cows milk.

T_{ag} (kg^{-1} m^2)	Source of radiostrontium	Comments	Reference
$13x10^{-3}$**	^{85}Sr sprayed onto pasture	Permanent pasture	Calculated from van den Hoek & Kirchmann (1968)
$13x10^{-3}$**		Reseeded pasture	
$16x10^{-3}$**		Rotationally grazed*	Calculated from van den Hoek et al (1969)
		State Farms	Nikipelov et al (1989)
$0.032x10^{-3}$	Kystymn fallout	1971-72	
$0.023x10^{-3}$		1976-80	
$0.015x10^{-3}$		1981-85	
$0.012x10^{-3}$		1986-88	
		Private Farms	
$0.22x10^{-3}$	Kystymn fallout	1971-72	
$0.11x10^{-3}$		1976-80	
$0.15x10^{-3}$		1981-85	
$0.14x10^{-3}$		1986-88	
$(0.7\text{-}2.5)x10^{-3}$	Chernobyl fallout	Ukrainian Polesye	Averin 1994
$(0.07\text{-}0.7)x10^{-3}$		Kiev Region	
$3x10^{-3}$	Chernobyl fallout	1987; soil pH=4.5-5.5	Prister et al. 1990.
$2.5x10^{-3}$		1988	
$3x10^{-3}$		1989	
$3.4x10^{-3}$		1990	
$1.9x10^{-3}$	Chernobyl fallout	1987; soil pH=5.6-6.5	Prister et al. 1990.
$1.4x10^{-3}$		1988	
$1.0x10^{-3}$		1989	
$1.2x10^{-3}$		1990	
$0.9x10^{-3}$	Chernobyl fallout	1987; soil pH=6.6-7.2	Prister et al. 1990
$0.5x10^{-3}$		1988	
$0.4x10^{-3}$		1989	
$0.2x10^{-3}$		1990	
$6x10^{-3}$	Chernobyl fallout	max value reached after 12-16 days following contamination (St. Petersburg region)	Shutov et al. 1993
$2x10^{-3}$		Value at 52 days after contamination	
$(38\pm2)x10^{-3}$	Chernobyl fallout	Fuel particles present	Howard et al .1993

* Mean value for animals rotationally grazed on both permanent and reseeded pastures.

** Measured over days 5-11 after contamination.

***Measurements were conducted within the Ukraine.

3 COUNTERMEASURES

3.1 INTRODUCTION

Countermeasures need to be considered if the activity concentration of a radionuclide exceeds the intervention limit. In EC countries the intervention limit, or maximum permitted level, for isotopes of strontium in dairy products is 125 Bq kg^{-1} (Commission of the European Communities 1987; National Radiological Protection Board 1994). Therefore, it is important to have effective countermeasures available to reduce contamination levels in milk and prevent milk with radiostrontium activity concentrations exceeding intervention limits from entering the foodchain. Control of radiostrontium levels in milk is particularly important for the critical group of suckling infants. Exposure of the human population to radiostrontium via ingestion of milk can be considerably reduced by the imposition of appropriate controls.

Countermeasures which can be used to limit radionuclide contamination in animals can be divided into four categories according to Hove et al. (1993):

• limiting the intake of radionuclides,
• reducing the absorption of ingested radionuclides in feed,
• blocking the uptake into and transport through organs,
• increasing the excretion of a previously accumulated body burden.

For radiostrontium the most effective countermeasures belong to the first two categories. Although there is an extensive literature on the potential use of chelators to reduce body burdens, these have not been considered here. Little attention is given in these reports, which are primarily concerned with the reduction of bone irradiation, to the potential effect of chelation on ^{90}Sr levels in milk. However, removing ^{90}Sr from bone by chelation may increase ^{90}Sr levels in milk.

A number of countermeasures are generally applicable for use against a wide range of radionuclides and those relevant for use against radiostrontium transfer to milk are discussed below. Soil-based countermeasures, although of general applicability for various radionuclides, have been considered for radiostrontium in particular and are therefore included in the subsequent section on measures specific to radiostrontium. For all the countermeasures discussed an overriding consideration will be the magnitude of the problem, some measures will be much more applicable and practical for small-scale scenarios, and others would probably only be considered in the event of a large-scale accident with many thousands of hectares of land heavily contaminated.

3.2 GENERAL COUNTERMEASURES

General countermeasures can most conveniently be divided into two categories, (i) those suitable over the short term, when animals are ingesting intercepted fallout, and radiostrontium contamination levels in milk will be substantially influenced by the original amount of deposited fallout, and (ii) those required over the longer term, which will be needed in areas of either high deposition, or where soil to plant uptake is high enough to maintain persistently high levels in vegetation, and hence milk. Countermeasures listed first would be considered in the short term. Countermeasures which need to be carried out quickly after an accident have to be simple, easy to carry out procedures. It should be possible for farm-based procedures to be carried out by large numbers of farmers with little instruction, using resources which are normally available or easily supplied. It must be remembered that there will almost always be more than one radionuclide in the fallout and countermeasures used at this stage tend to be effective for a wide range of different radionuclides.

The proportion of radiostrontium which is intercepted by vegetation and the rate at which it is lost from the surfaces determines the potential effectiveness of many countermeasure techniques which are appropriate for the early stages after an accidental release. Much of the radiostrontium retained on plant surfaces will be lost, through weathering processes such as washing off by rainfall or resuspension, within the first month after deposition. Therefore, the extent of interception and retention on plant surfaces is important in determining both the duration and extent of high radiostrontium levels in milk. The obvious exception is where plant uptake of radiostrontium is high and sustained, or where there is an additional significant source of radiostrontium, for instance via ingested soil. Therefore, persistently high levels of ^{90}Sr in milk will occur in areas with high deposition, or where soil types allow high rates of radiostrontium uptake. Recent estimates of the ecological half-life for plant availability of radiostrontium in Scandinavian grasslands give values of an initial half-life of 1-2 y, followed by a longer component of up to 28 y (Eriksson 1994), but these would be expected to vary considerably with soil type.

3.2.1 Provide uncontaminated feed or pasture

The most comprehensive and simple short term countermeasure that is effective for almost all radionuclides is to restrict or prevent animals from eating contaminated forage or herbage. This can be accomplished either by:

i) preventing grazing of contaminated pasture by keeping animals indoors or in enclosed areas, and providing uncontaminated feeds; or

ii) moving animals to uncontaminated pasture.

For the situation where milk is likely to become contaminated with radiostrontium above the intervention limits then preventing the animals from ingesting contaminated herbage is amongst the simplest and most effective countermeasure available. An additional benefit from these countermeasures is a reduction in irradiation of bone.

Housing animals which would normally be grazing outdoors (or preventing the return of stalled animals to pasture) and providing uncontaminated forage to prevent ingestion of contaminated herbage is simple to carry out in the UK dairy industry. The effectiveness of this response will be highly dependent on the nature and extent of the contamination, and also on the period between exposure and evacuation. Ideally, uncontaminated feedstuffs need to be made available rapidly and appropriate management of on-farm feeding regimes would need to use uncontaminated feed in the most cost-effective way. When supplies of uncontaminated fodder are limited, priority should be given to supplying uncontaminated forage continuously to dairy cows, in preference to beef cattle, sheep or pork, so that acceptable milk can continue to be produced. Availability of stored, uncontaminated fodder will vary; availability may be limited in late spring and early summer prior to the normal fodder harvesting time in the UK. The provision of uncontaminated feed, either from UK sources or imports may incur substantial additional costs, and will take some time to arrange. Equally, if stored feeds were used precipitately during the grazing season, these would need to be replaced before the autumn.

A ban on grazing should only be lifted after a detailed description of the composition and extent of the fallout has been obtained, and when radiostrontium activity concentrations in pasture grass are low enough to produce milk with radiostrontium activity concentrations below intervention limits. Likely reductions in radiostrontium levels in both grass and milk can be predicted using mathematical models. Such predictions may need to be verified by allowing cows onto contaminated pasture and monitoring radiostrontium activity concentrations in the resulting milk.

The capacity to move animals to uncontaminated pastures would depend on the availability of such land and may need to be continued for a long period of time. In the UK the availability of alternative land for grazing would probably be very limited, and the capacity to move animals would depend on the number of animals involved. It would be impractical and expensive to move large numbers of dairy animals to uncontaminated areas, and then support the management of twice-daily milking.

3.2.2 Change the harvesting time of forage crops

Depending on the time of year in which deposition occurs the removal of foliage may be considered. There are two potential approaches :

(i) rapid removal of forage crops to remove a significant proportion of the intercepted fallout

If standing above-ground vegetation is harvested before the intercepted fallout was lost from the plant surfaces, a significant, but highly variable (depending on interception rates) proportion of the total deposit would be prevented from reaching the soil. This would thus reduce total deposition remaining in the soil, and thereafter available for plant uptake. The procedure of removing vegetation would be comparatively easy in the UK as the necessary machinery is widespread. The radiation doses and possible concerns of farmers who may be asked to carry out the removal also needs to be considered. However, the radioactive crop would need to be disposed of and, depending on the scale of the accident, it may be difficult to identify suitable disposal routes. Consideration would need to be given to the suitability of normal landfill sites, or possible use of nuclear sites disposal facilities.

The lost animal feedstuff production would need to be replaced.

(ii) delaying harvesting of forage to allow removal by weathering of the fallout intercepted by vegetation surfaces.

This could significantly decrease the radiostrontium content of forage, which is subsequently intended to be fed to housed animals. Both the extent of deposition, root uptake and interception (which would vary with season) would need to be considered before harvesting was delayed.

3.2.3 Destruction of animal products

Destruction of animal products prevents highly contaminated products from entering the human foodchain. As above, suitable collection and disposal of highly contaminated milk would need to be considered and arranged; some disposal routes may not be socially and environmentally acceptable. Destruction is very expensive, both in terms of the loss of product and the manpower needed, and should only be used in exceptional circumstances.

3.2.4 Removal of soil

Radioactive contamination remains in the top soil layers for a long time, and therefore removal of the top soil layer can potentially remove most of the contamination. This countermeasure was used extensively in the CIS after the Chernobyl accident. Equipment needed to carry out soil removal should be readily available and currently available equipment would remove the top 5-10 cm of soil. However, the removal of soil, particularly in the event of a large-scale accident, is extremely costly and would generate large volumes of radioactive waste. In addition, soil fertility would be considerably reduced.

Recently a turf harvester, which removes only the top 1-2 cm of soil thereby minimising the above problems, has been developed in France (Jouve et al. 1993). Preliminary trials with the harvester in Ukraine have been promising, but further testing is required, and the consequences for nutrient loss in UK pasture systems would need to be assessed. The turf harvester could not be used with stony soils, but may still be usable for a significant proportion of UK agricultural soils. The cost effectiveness of the technique for UK conditions would also need to be assessed.

The use of peelable coatings which are sprayed or painted onto soil and allowed to dry. The solvent then evaporates leaving a thin plastic film which can be peeled or scraped off with adherent top soil. Such an approach has been tested for both agricultural (Jouve et al. 1993) and urban environments (Andersson & Roed 1994). These coatings may provide an effective and cheaper alternative to other methods of soil removal, but are most suitable for small-scale restoration. Tests in UK conditions for the most promising substances, with appropriate radionuclides would be needed.

3.2.5. Ploughing

Ploughing can either move the top layer of contaminated soil deeper down the soil profile, or mix the top layer with the rest of the soil, thereby reducing the radiostrontium activity concentration in the soil layers where plant roots occur. Ploughing will reduce external exposure and minimise potential resuspension, and may be particularly useful for enriched, fertile, buffered soils, where the transfer of radiostrontium is already low, and the chemical effects of soil treatments may be insignificant.

i) Shallow ploughing

Shallow ploughing, which could be applied easily and cheaply throughout the UK, is useful in the first year after an accident as it removes the radioactive contamination from the rooting zone of many forage crops and pasture grasses. Shallow ploughing would be most beneficial, and least disruptive to the UK farming economy if it is carried out either outside the growing season, or in the early spring. The disadvantages of shallow ploughing are three-fold in that (i) radioactive contamination in the top 0-25 cm would still be available to most crops, albeit significantly diluted, (ii) ploughing in subsequent years would tend to return the radioactive contamination to the soil surface, and (iii) there would be a reduced yearly forage yield as the pastures/forage grasses would need to become re-established.

Further consideration might be given to the different methods of surface ploughing which are available, to see whether some of the above disadvantages might be overcome. Given the accessibility of surface ploughing within the UK the potential benefit versus disadvantage should be considered for different types of crop/land use.

ii) Deep ploughing

Deep ploughing, which can remove top soil to about 30 cm below the soil surface, obviously removes the contamination from the rooting zone. Special ploughs would be needed, which would be expensive, both to purchase and use. This technique has the considerable disadvantage that it greatly reduces soil fertility by removing most of the top soil, and replacing it with infertile soil from deeper layers. Deep ploughing to deeper layers can also destroy land drainage systems.

iii) Skim and burial ploughing

A skim and burial plough has been developed in Denmark which skims the top 5 cm from the soil surface and places it beneath the next 5-50 cm soil layer. This has the advantage that the soil is not inverted and comparatively fertile soil remains at the surface rooting zone. It is therefore potentially useful for many agricultural soils, with the exception of shallow, stony soil or potentially waterlogged soils. Normal ploughing can continue without bringing the contaminated layer to the surface. The procedure therefore reduces both radionuclide uptake and external doses substantially. The ploughs would need to be purchased from Denmark, at a price of about £3,500 each, or alternatively manufactured in the UK.

3.2.6 Using contaminated land for non-dairy animals

Changing from milk to meat production, or raising breeding stock, maintains usage of contaminated land, which is too highly contaminated to be used for dairy animals (Jones 1993). This was one of the main countermeasure strategies adopted in Russia after the Kyshtym accident, and allowed vast areas of farmland to continue in the production of animal products (Romanov et al. 1990). Areas with ^{90}Sr deposition exceeding 74 kBq m^{-2} were devoted to meat production.

In the UK the potential for this approach is severely limited, and could only be considered on a small scale (Nisbet 1995a). There may be an imbalance between supply and demand of cattle products, if more beef was produced. Furthermore, there would be a reduction, rather than increase, in the supply of calves for beef if milk production was reduced.

3.2.7 Altering animal species

When small ruminants such as sheep and goats graze the same pasture as cattle, radiostrontium levels in milk will be higher in the smaller ruminants. Preference should therefore, theoretically, be given to dairy cows. However, this measure would be impractical in the UK, since there are relatively few dairy goats and sheep.

3.2.8 Diverting animal products from human to animal consumption

Contaminated milk, with radiostrontium contents exceeding intervention levels, could be fed to fur-producing animals or to domestic animals. The capacity for such an approach would be limited in the UK, because the capacity of the few fur retailing business to use the milk is very small, and the use of contaminated milk for domestic animals would probably be socially, commercially and politically unacceptable.

3.3 SPECIFIC COUNTERMEASURES FOR RADIOSTRONTIUM

3.3.1 Soil-based countermeasures

Countermeasures directed at reducing radionuclide uptake from soil are particularly important for situations where significant, long-term uptake of radionuclides from soils may occur. The countermeasures discussed below are methods of treating soil to reduce uptake of radiostrontium by pasture grass, silage, hay, and grains (which would be given as concentrates).

<u>Soil fertilisation</u>

Stable isotopes of strontium are normally present within the environment and typical concentrations of Sr in plant material of 26 mg kg^{-1} (dry weight (dw)) are quoted by Bowen (1966). Recent measurements of Sr levels in feedstuffs by Hansen et al. (in press) found values ranging from a low value of 3 mg kg^{-1} dw for barley, and 10-24 mg kg^{-1} dw for other feedstuffs including hay, soybean meal and concentrates.

Radiostrontium in soils will be present as the cation Sr^{2+}. The chemical behaviour of Sr^{2+} is similar to that of Ca^{2+}, since they are both alkaline earth elements with similar ionic radii (ionic radius of 0.132 and 0.118 nm respectively). There is no evidence for strong, specific fixation of radiostrontium in soils, and larger cations such as Sr^{2+} are restricted to ion exchange on the surface of clay minerals, organic matter and other soil constituents, which together make up the majority of the cation exchange capacity (CEC) of a soil. The behaviour of Sr^{2+} in soil is therefore determined by surface ion exchange equilibria. The range of agricultural soils in which there could be potentially high rates of plant uptake of radiostrontium is therefore much greater than that for radiocaesium. In general, radiostrontium will be more available in soils with a low CEC. Hence radiostrontium uptake rates are characteristically high in sandy, mineral or acidic soils, where the low pH may reduce the cation retention capacity of the soil. In contrast to radiocaesium, ^{90}Sr uptake from UK peaty soils has been found to be an order of magnitude lower than that of loam or sandy soils (Nisbet & Shaw 1994). In particular sandy soils with low pH are thought to be soil types which will allow maximum plant uptake of radiostrontium.

Radiostrontium may potentially be leached down soil profiles more readily than radiocaesium. Squire (1966) found that radiostrontium moved faster down soils with a high exchangeable calcium content (>20 milliequivalents (meq) Ca 100 g^{-1} - which will saturate the exchange sites, limiting the capacity to bind Sr^{2+}, and slowest in a clay soil (<3 meq Ca 100 g^{-1}) which presumably has many exchange sites available to bind radiostrontium.

The environmental transfer rates of radiostrontium are dominated by its relationship with calcium, and its behaviour in the environment and response to countermeasure treatments must always be considered with regard to calcium. Plants have a finite capacity to take up calcium, and therefore additions of calcium can be applied to soils to increase the exchangeable calcium levels in the soil solution, thereby decreasing the Sr^{2+}:Ca^{2+} available to plant roots. The CEC and Ca-saturation of soils largely determines the potential reduction in radiostrontium uptake by plants that can be achieved by liming, or the addition of other Ca-containing minerals. Liming in excess of the CEC generally fails to further reduce the radiostrontium level in plants (van Dorp et al. 1981). For the selection of suitable soils which would benefit from the addition of calcium the following criteria need to be considered, according to Nisbet et al. (1993):

1. Exchangeable calcium and base saturation of the contaminated soils.

The reduction factor which can be achieved is dependent on these two parameters. Soils with a low calcium and percentage base saturation status will show the greatest response to lime applications, potentially resulting in substantial reductions in radiostrontium uptake.

2. Sr/Ca selectivity in the contaminated soils

In soils where Sr is adsorbed in preference to Ca, the addition of Ca will be an effective countermeasure. In contrast, in soils which preferentially adsorb Ca any additional calcium in the soil may displace radiostrontium from exchange sites thereby increasing radiostrontium concentrations in soil solution, and hence plants. Soils with a high mineral content generally adsorb Sr preferentially, making calcium addition an effective countermeasure. For soils with a significant content of organic matter this is not necessarily true, and it would be necessary to confirm that Ca was not preferentially adsorbed, prior to treatment.

3. Calcium concentrations in the soil solution and their relationship to radiostrontium uptake by plants

Uptake of radiostrontium is related to the ability of plants to take up calcium, which in turn depends on the Sr^{2+}:Ca^{2+} in the soil solution. The observed ratio between soil solution and plant tissues varies between 0.7 and 1.4 for different species. Generally, however, there is no significant discrimination in the uptake of strontium and calcium by plants over a wide range of Sr^{2+}:Ca^{2+}. Consequently, increasing the available calcium pool in the soil will decrease the radiostrontium uptake by plant roots. In soils with an initially low soil solution concentration of calcium (i.e. 2 meq exchangeable Ca 100 g^{-1} soil) there will tend to be a larger response to applied calcium than that of soils with a relatively high calcium status (i.e. >10 meq exchangeable Ca 100 g^{-1} soil).

Data available on the effectiveness of soil-based treatments come from (i) experiments conducted on a small scale under controlled conditions (summarised by Lembrechts 1993) and (ii) large scale studies in contaminated environments, including the areas contaminated by the Kyshtym and Chernobyl accidents (Konoplev et al. 1993; Prister et al. 1993; Alexakhin 1993).

A summary of the main treatments and their effect is given in Nisbet et al. (1993), and is reproduced in Table 3.1.

Recent studies by Nisbet (1995b) found that lime did have an ameliorative effect in acid, organic UK soils, and therefore the caveat in the table regarding organic soils may not be a problem for the specific soil types used by Nisbet.

Generally higher reduction factors have been achieved for soils with a poor fertility status. For instance, soil treatments were particularly effective in some areas of Russia, Ukraine and Belarus affected by the Chernobyl accident, where the increase in fertility also led to increased biomass production, thereby enhancing the reduction in ^{90}Sr activity concentrations in plants. Reduction factors of about 10 reported for certain crop/soil types in the former Soviet Union would not be expected in the UK, where soil fertility is much higher.

The treatments given in the Table use substances which are readily available in large quantities, inexpensive and easy to apply. The effectiveness estimates relate to the use of application rates in excess of those normally used in agricultural practice, especially for lime. For example, lime is usually applied at a rate of 3 t ha^{-1}, whereas in experiments rates of between 2 and 100 t ha^{-1} have been used. The use of quantities greatly in excess of normal practice may have adverse consequences as it will not greatly improve effectiveness, but may well decrease availability of many other essential micronutrients in the soil.

It is very difficult to generalise about recommended rates for application of the various soil treatments, although it would probably be advisable to use rates which were only 2-3 fold greater than that normally used. Nisbet (1993) gives the following guidelines for land which is contaminated by radiostrontium:

1. Identify soils with a low exchangeable calcium content and a low percentage base saturation

2. Determine selectivity coefficient ($^{Sr/Ca}Kc$) of these "problem" soils

3. Identify soils that should respond to liming ($^{Sr/Ca}Kc > 1$)

4. Avoid joint application of lime and organic matter to mineral soils

5. Conduct batch equilibrium studies on soils to be treated to determine the effects of different treatments on radiostrontium desorption and Ca:radiostrontium ratios in solution.

Obviously such analysis would take some time, and such detailed assessment is unlikely to be available for many soil types, prior to an accident.

In the UK, Milbourn (1960) found that radiostrontium uptake from soils with greater than 5 meq Ca 100 g^{-1} soil was not markedly reduced by the addition of more calcium. Recently, Nisbet et al. (1994)

confirmed that for 3 soils with Ca contents above this value the addition of Ca had no effect on the $^{90}Sr^{2+}$:Ca^{2+} quotients in batch equilibria experiments.

It is important to consider the effect of soil treatments on other potential radionuclide contaminants which may be present after a nuclear accident. The probable effect of various soil treatments on availability of both radiocaesium and radiostrontium was summarised by Nisbet (1993) in Table 3.2.

Table 3.2. Probable effect of soil treatments on availability of radiocaesium and radiostrontium from mixed deposits (after Nisbet 1993).

Soil Type	Treatment	Probable effect	
		Radiocaesium	Radiostrontium
Mineral	Potassium	Beneficial / deleterious	Beneficial *
Organic	Potassium	Beneficial	Beneficial *
Mineral	Calcium	Beneficial (with K)	Beneficial
Organic	Calcium	Beneficial (with K)	Possibly deleterious
Mineral	Organic matter	Deleterious	Beneficial (no Ca)

* based on limited information

3.3.2. Pasture- based countermeasures

The obvious pasture-based countermeasure which can be carried out whilst animals are grazing pasture is to lime the field. Van den Hoek & Binnerts (1967) reported that liming a field with two different sorts of Ca compound resulted in 30-35% reductions in radiostrontium activity concentrations in milk. Although Ca intake was not measured the increased Ca content of faeces from treatment cows suggested that Ca intake by this group had increased by 1.5 - 2 fold compared with the controls. The reduction response was rapid, with a 20% reduction occurring within 10 h, and a 30% reduction within 4 days. The cows seemed to have no problems of palatability of the grass, or willingness to continue grazing, with application rates of 500 kg ha^{-1}, equivalent to 35 and 48 g Ca m^{-2} for the two compounds.

3.3.3. Vegetation based countermeasures

It may be possible to select optimum types of animal feedstuffs which would give comparatively low F_m values for radiostrontium, on the basis of either a low radiostrontium level in the plant (through low soil to plant transfer), or a naturally high calcium content. Theoretically it may be possible to select certain species of fodder and pasture grasses, root fodder crops or grains which would be less contaminated by radiostrontium than those currently in use in the UK. Grains have a relatively low uptake of radiostrontium, compared with that of root crops, fodder and grass (IAEA 1994b), and transfer to leguminous species is generally 2.4 fold higher than that to herbaceous species (Annenkov 1964a). On this basis it would be tempting to suggest that the proportion of concentrate in a dairy animals diet should be as high as possible. However, such selection must always take account of any possible reduction in Ca content; if there is also a concomitant reduction in Ca intake then there may be no overall beneficial effect on radiostrontium levels in milk.

Some studies have been carried out in the former Soviet Union to look at the transfer of ^{90}Sr from different types of vegetation. Annenkov (1964a) compared the transfer to milk of ^{90}Sr from meadow grass, grain and leguminous (bean) hay. The results are given in Table 3.3.

Table 3.3 Comparison of the transfer of ^{90}Sr to milk in dairy cows fed part of their diet containing different feedstuffs contaminated with ^{90}Sr (after Annenkov 1964a)

^{90}Sr source	n	milk yield (l)	F_m (d l^{-1})*
Meadow grass	3	8.6	0.00152±0.015
Grain	4	9.2	0.00139±0.006
Leguminous hay	4	9.1	0.00119±0.009

* mean ± unspecified error

The influence of fodder type was not great, and although the lower F_m measured for leguminous hay was significantly different to the other feedstuffs, the use of this fodder was not recommended because of its high ^{90}Sr uptake rate from soil, which was quoted as being 2-4 fold higher than that of herbaceous vegetation.

Another fodder experiment by Buldakov et al. (1964) compared the transfer to milk of ^{90}Sr from oats and vetch, and the results are presented in Table 3.4. The milk yield for each treatment was similar.

Table 3.4 Comparison of the transfer of ^{90}Sr to milk in dairy cows fed oats and vetch (after Buldakov et al. 1964).

^{90}Sr source	n	Ca intake (g d^{-1})	Lactation yield	F_m (d l^{-1}) (Mean)
Oats	4	30	7-8	0.0027
Vetch*	4	70	7	0.0012

*Vetch is a small legume

The transfer coefficient for cows fed oats was significantly greater than that for the cows fed vetch; this was probably due to >2 fold difference in Ca intake, caused by the different calcium content of the fodders.

In studies conducted in the 1960's Garner (1971) observed that the F_m for dairy cows fed fallout ^{90}Sr in alfalfa hay (i.e. lucerne) was much lower, at 0.0005 to 0.0009 d l^{-1}, than that of 0.002 to 0.0022d l^{-1} measured for dairy cows pastured on clover, orchard grass and rye grass. The difference may have been due to the high natural calcium content of lucerne.

In field experiments conducted by Korneev et al. (1973) radiostrontium transfer to milk in cows grazing a natural meadow was found to vary, depending on different fodder types given to the cows. A meadow, presumably contaminated by the Kyshtym accident, was divided into three plots, with the aim of providing fodder for experimental cows:

- left as a natural, unimproved meadow, with 95% of the ^{90}Sr in the top 0-5 cm soil layer. Cows grazed on the pasture in spring/summer and given hay from the natural meadow in autumn/winter.
- the meadow was deep ploughed to a depth of either 25-30 cm or 50-60 cm, and reseeded with cultivated plants, which provided fodder for the cows.

Housed dairy cows received either mixed or concentrated ^{90}Sr contaminated rations from fodder grown on the second and third treatment meadows. These feeds constituted only part of the total ration of the cows. The highest ingestion rate of ^{90}Sr occurred when the cows were pastured outside, and was thought to be due to higher consumption rates of fodder and consumption of contaminated top soil. The ^{90}Sr activity concentration in milk from cows grazing outside was 40% higher than that of housed cows. Stabling of cows throughout the year allowed a much stricter control of ^{90}Sr intake, producing milk with a much more consistent contamination level. The amount of ^{90}Sr secreted in milk gradually increased over the three year period (Table 3.5), and was thought to be due to a gradual increase in the amount of ^{90}Sr in bone.

Table 3.5. Effect of type of ration and duration of ingestion on F_m of radiostrontium to cow milk (after Korneev et al. 1973).

Type of ration	Duration of contamination (y)	Ca content of ration ($g\ d^{-1}$)	F_m* ($d\ l^{-1}$)
Hay	1	41	0.0016±0.0002
Mixed	1	45	0.0014±0.0001
Concentrate	1	25	0.0033±0.0009
Hay	2	60	0.0015±0.0001
Mixed	2	56	0.0017±0.0001
Concentrate	2	50 (25 g Ca added)	0.0025±0.0001
Hay	3	48	0.0018±0.0001
Mixed	3	44	0.0023±0.0002
Concentrate	3	18	0.0046±0.0004

* mean ± unspecified error

The F_m value for cows fed grain as concentrate was greater than for the cows fed a mixed or hay ration, and this was attributed to the lower calcium content of the grain ration of these cows.

A few studies on varietal differences in radionuclides uptake have been conducted, primarily in the former Soviet Union, and reasonably good reduction factors for radiocaesium have been reported (Alexakhin et al. 1993). However, available information is currently inadequate to identify varieties of crops with low transfer ratios for soil to plant uptake of radiostrontium, which would be appropriate for the UK. Furthermore, for a long term countermeasure factors such as disease and pest resistance, and yield would need to be considered (Nisbet 1995a).

Effective reductions in the transfer of radiostrontium to milk can be achieved by appropriate changes in husbandry. These measures are aimed at reducing the intake of radiostrontium and maximising the intake of calcium by the animals. The effectiveness of these measures depends to a large extent on the original fertility of the land, and the nutrient status of the animals. Much of the relevant information comes from the former Soviet Union and arises from the response to the Kyshtym accident, where data from the experiments described above was used to minimise ^{90}Sr activity concentrations in milk. In the affected areas 70-80% of the daily ^{90}Sr intake came from milk (Romanov et al. 1990).

Radioactive produce was monitored in areas where habitation continued (where ^{90}Sr levels were below 74 kBq m^{-2}), and rejected when it exceeded intervention levels, but this measure had little effect in reducing doses because it was applied rather late (the accident occurred in October 1957 and the monitoring took place from the summer of 1958) and was difficult to implement (Romanov et al. 1990). Radiation protection largely involved reducing the ^{90}Sr levels in milk of private cows. This was achieved by banning the use of unimproved pasture and hay meadows, where ^{90}Sr uptake was much higher than on collective farm land. This measure was estimated to reduce ^{90}Sr intake by residents by a factor of two. In areas where ^{90}Sr deposition exceeded 74 kBq m^{-2} agricultural production was restored by setting up state farms specialising in the production of meat (beef and pork), which produced meat with 2.5 - 5 fold lower ^{90}Sr activity concentrations than that from surrounding areas. For dairy animals reductions in milk contamination were achieved by the following measures:

Selecting optimum composition of fodder ration	gave a 10 fold reduction
Increasing the yield of dairy cattle	gave a 0-10 fold reduction

The most sensible measure was thought to be altering the fodder ration to include feed with low ^{90}Sr activity concentrations, and high nutritional value. In particular fodder from unimproved, natural pasture was avoided.

3.3.4 Animal based countermeasures

The countermeasures are generally intended to reduce absorption of radiostrontium in the gut, thereby reducing transfer to milk, although they will have the additional benefit of also reducing deposition in bone. An important criteria when considering potential additives, particularly if they are to be considered as long-term countermeasures, is that they must not prevent essential elements, including calcium, from being absorbed in the gut. The countermeasures considered below fall into two groups:

(i) Competitive ions

- which will compete with radiostrontium for absorption and transfer to animal tissues and milk.

(ii) binders

- which will adsorb the strontium ions sufficiently strongly to reduce absorption in the gut. The identification of suitable substances which might bind strontium is difficult, because of its close chemical resemblance to calcium. Many substances, unless they have a relatively highly specific preference for strontium ions will be swamped by the overwhelming amount of calcium ions present in the gut. Moreover, chelation of alkaline earth ions is governed by ionic radius; the stability constant is an inverse function of the ionic radius, and hence strontium chelates are less stable than calcium chelates. Potentially effective substances would include those which (i) form insoluble compounds with strontium in the presence of calcium under physiological conditions, or (ii) bind cations by ion exchange, and might bind strontium more strongly than calcium in the physiological range of salt concentrations. It is important to consider the potential effect of binders on calcium ions. If the binders reduce calcium absorption they may lead to calcium deficiency, which could lead to desorption of both calcium and radiostrontium from bone. Hence binders which have the potential for calcium binding would probably only be suitable for the short term, and not over long periods, particularly when animals have been previously contaminated with radiostrontium, which would be resident in the bone.

i) Stable calcium

In this section the supplementation of feed with additional calcium which is given directly to housed animals is considered. There have been many experiments on the effect of Ca on ^{90}Sr transfer to non-lactating small vertebrates, but in this review only those experiments considering the effect of Ca on ^{90}Sr levels in milk of lactating ruminants have been considered.

Studies in the former Soviet Union have shown that the addition of $CaCO_3$ to the diet of calves and cows reduced the whole body levels of ^{90}Sr by 40% and 43% respectively and that bone accumulation of ^{90}Sr by cattle is related to age and levels of Ca intake (Annenkov et al. 1973). The effectiveness of increasing Ca intake in reducing ^{90}Sr accumulation in bone increases with age, and depends on the Ca requirement as determined by the rate of bone mineralization. In calves aged 1, 3 and 6 months old, 85%, 52% and 33 % respectively of a ^{90}Sr dose was deposited in the skeleton. The addition of $Ca_3(PO_4)_2$ doses (of 16-27g giving total daily dietary intakes of 23-35 g d^{-1}) to the diet of these calves reduced ^{90}Sr deposition in the bone by factors of 1.3, 1.5 and 1.9 respectively.

Sirotkin et al. (1969) found that reducing Ca intake from 40 g d^{-1} to 16 g d^{-1} had no initial effect on ^{90}Sr levels in milk after an oral single administration of ^{90}Sr (Table 3.6). After 25 days ^{90}Sr levels in milk of cows receiving a low Ca intake was approximately three fold higher than those receiving the normal Ca intake. Cows on the lower dose produced calves with c. 40% higher ^{90}Sr contents in the skeleton.

Table 3.6 Effect of reducing Ca intake on transfer of ^{90}Sr to cow milk with time (Sirotkin et al. 1969).

Group	n	Ca in ration ($g\ d^{-1}$)	^{90}Sr in milk (% of dose l^{-1}) (mean ± error) Time after administration of a single dose				
			12 h	1 d	5 d	15 d	25-330 d
Control	2	Normal (40)	0.78 ±0.08	0.39 ±0.04	0.015 ±0.003	0.02 ±0.0005	0.0001 ±0.00003
Exp.	3	Low (16)	0.78 ±0.14	0.45 ±0.08	0.016 ±0.003	0.03 ±0.0006	0.0003 ±0.00004

In initial studies reported from the former Soviet Union the addition of substantial amounts of Ca (400g of $CaCO_3$) to the diet of dairy cows was reported by Annenkov (1964b) to reduce ^{90}Sr activity concentrations in the milk by only 30-35%. Annenkov (1964b) also reported that the effectiveness of calcium addition in reducing radiostrontium transfer also depended on the calcium salt. The salts had the following order of diminishing effectiveness:

$$Ca_3(PO_4)_2 > CaO\ ,\ Ca(COO)_2 > CaCo_3 > Ca\ (C_3H_5O_3)_2.$$

It is unclear what compound is referred to by the formula $Ca(COO)_2$.

Comparisons of ^{90}Sr transfer to milk of cows on a very low, and somewhat higher calcium intake, via fodder, have also been reported from the former Soviet Union. In Annenkov et al. (1973), F_m values for ^{90}Sr of 0.018 d l^{-1} to 0.0005 d l^{-1} were given for dairy cows fed Ca within fodder at a rate of 12.5 g d^{-1} and 120 g d^{-1} respectively, equivalent to an F_m which is a factor of 24 lower for the higher Ca intake cows. When Ca was additionally fed in a mineral form, with a consequent daily Ca intake of 128 g d^{-1} the F_m value was 0.003 d l^{-1}, indicating that there was a reduced absorption of ^{90}Sr in the gut, when compared with the when stable Ca was given fodder. Similar conclusions were drawn for the bone and soft tissues of the experimental cows.

Feeding experiments were also conducted in Germany, where feeding of Ca to dairy cows at three different levels of 0.25%, 0.5% and 1.3% of the diet gave respective F_m values for ^{85}Sr of 0.0014, 0.0008 and 0.0004 d l^{-1} (Hill 1966). The addition of calcium increased urinary and faecal excretion of ^{45}Ca, but had no effect on urinary and faecal excretion of ^{85}Sr.

Two of the most comprehensively reported experiments on the effects of Ca supplementation on radiostrontium transfer to milk were carried out by Comar et al. (1961; 1966a). The first series of experiments were conducted over a 9-10 d period whereas the latter experiments were long-term feeding trials conducted over a 2 year period

In the first study the effects of feeding three diets containing calcium at 0.25%, 0.5% and 1.6 or 1.7% on the transfer of ^{89}Sr, given twice daily, to dairy goats and cows (n=2 for each treatment) was investigated. With goats plateau levels of ^{89}Sr in milk were reached by the third day of dosing, in the cows this took 4-6 d. Since a pseudo-equilibrium was attained, transfer coefficient values could be calculated and are shown in Table 3.7

Table 3.7 Reduction in the transfer coefficient, F_m, for ^{89}Sr to goat and cow milk (after Comar et al 1961).

Treatment	Goats		Cows	
Ca level in diet	Daily Ca intake (g)	F_m (d l^{-1})	Daily Ca intake (g)	F_m (d l^{-1})
Low (0.25%)	4.9	0.017	45	0.0014
Normal (0.5%)	10.6	0.014	90	0.0008
High (1.7%g goats; 1.6% cows)	36.0	0.0074	281	0.00041

Caution must be used in interpreting the results as there were only 2 animals on each treatment and variation within treatments for many results was not presented. Similarly no statistical analysis of the data was attempted.

Increasing the calcium level of the diet reduced the F_m by similar proportions in both species. There was no effect on the $OR_{milk\text{-}diet}$ values for either species and this led the authors to suggest that long term feeding of calcium to dairy animals should result in a proportional decrease in ingested radiostrontium in milk.

The second long-term experiment was carried out with dairy cows covering the period from 5 months to 2.5 y old (Comar et al. 1966a), and has the advantage that replication was adequate and errors quoted. Five dairy cows were placed on a "low calcium" diet and five on a "high calcium" diet at 5 months old. The "low" calcium diet was a normal commercial ration (and therefore the term normal is used here); for the "high" diet Ca supplementation was given as dicalcium phosphate to try and maintain similar Ca:P ratios in both treatments. The differing diets were maintained for 2 y, and transfer of ^{90}Sr from both nuclear weapons fallout (present in the ration) and tracer ^{85}Sr was measured in balance trials which started about 70d after gestation. A summary of the experimental conditions and results is given in Table 3.8

Table 3.8 Experimental criteria and transfer coefficients for cows given a "high" or normal calcium diet (mean ± SE) (after Comar et al. 1966a).

	High calcium	Normal calcium
Body weight		
initial	242 ± 24	212 ± 10
final	1119 ± 31	1213 ± 33
Milk production ($l\ d^{-1}$)	22.6 ± 0.9	21.8 ± 1.7
Ca intake ($g\ d^{-1}$)	121	54
Ca in milk($g\ l^{-1}$)	1.07 ± 0.04	1.07 ± 0.03
Transfer coefficient (F_m)		
^{90}Sr ($d\ l^{-1}$)	0.00074 ± 0.00008	0.0014 ± 0.0002
^{85}Sr ($d\ l^{-1}$)	0.00039 ± 0.000005	0.00073 ± 0.00008

There was no effect of Ca level in the diet on liveweight gain, or on the total amount of calcium secreted in the milk, since this was homeostatically controlled. Transfer coefficients for both strontium isotopes were reduced to the same degree in milk from cows on the "high" calcium diet compared with that of those on the normal calcium diet. The authors felt that this was an indication that the amount of radiostrontium in milk was inversely proportional to that in the diet, since a 2.24 increase in Ca intake led to a 1.91 decrease in ^{90}Sr in milk. However, further studies with a wider range of Ca intakes would be needed to verify the hypothesis.

A further consideration arising from Comar et al.'s (1966a) experiments is that by also giving ^{47}Ca and comparing the behaviour of this isotope with stable calcium the authors were able to identify the sources of calcium in the milk. In the "high calcium" cows 58% of the calcium in milk originated from the diet, whereas for cows on a normal diet 42% came from the diet. In common with other evidence this supports the observation that the higher the dietary calcium intake the lower the drain on body calcium for secretion in milk.

It is clear that the level of ^{90}Sr contamination in milk will depend on that in the diet and on the calcium level of the feed. Therefore simply adding calcium to a normally adequate diet would have a measurable effect, and radiostrontium levels in milk respond rapidly to those on the diet. The reduction in radiostrontium activity concentrations in milk may be affected by bone stores of radiostrontium after long-term contamination, because of the contribution of the bone store of calcium and radiostrontium to the milk.

The most logical approach in recommending supplementation rates of stable calcium which would be effective in reducing ^{90}Sr transfer to milk is to consider the normal calcium requirement of the lactating ruminant (see Table 2.2). It may be difficult to get dairy animals to consume large and adequate amounts of excess calcium each day (>100 g d^{-1} for a dairy cow) to have a reduction effect greater than a factor of 2.5, particularly over long time periods. An additional potential problem is that long periods of feeding with high rates of calcium may lead to reductions in absorption, and consequent deficiencies of major essential elements, including P, S, Mn and Zn.

ii) Stable strontium

There is contradictory evidence on the ability of stable Sr to reduce the deposition of radiostrontium in bone or its transfer to milk. Some studies in rats have shown a reduced uptake of radiostrontium in bone when the rats were given 6% strontium lactate in the diet for 5 d prior to an intraperitoneal injection of ^{85}Sr (Teree et al. 1965), but this also led to a diminution in growth.

Most authors have found little significant effect. For instance, in rabbits the presence of carrier Sr with injected radiostrontium had no effect on strontium retention or excretion (Kidman et al. 1950). Similarly, in rats the addition of small amounts of Sr for three weeks, sufficient to reduce the specific activity of the dietary ^{89}Sr by a factor of 4, had no effect on bone deposition. Larger amounts of stable Sr were no more effective than Ca, on a weight basis, in reducing the transfer of ^{89}Sr to bone (Hegstedt & Bresnahan 1963).

Comparisons of calcium and strontium levels in milk and diet by Comar & Wasserman (1964) showed that whilst increasing the calcium level in the diet from 54 g d^{-1} to 281 g d^{-1} did not significantly affect calcium milk levels an increase of a factor of 2700 for strontium intake, from 0.18 g d^{-1} to 490 g d^{-1}, led to an equivalent increase of Sr levels in milk, from 0.00022 to 0.588 g l^{-1}. In the stable calcium experiment described above by Comar et al. (1961) a further treatment was included where additional stable strontium was given to the goats and cows and the effect compared with that for stable calcium alone. The results are given in Table 3.9.

Table 3.9. Comparative effect of calcium and strontium in the diet on ^{89}Sr transfer coefficients for goat and cow milk (after Comar et al 1961).

Ca + Sr treatment	Goats		Cows	
	Daily Ca +Sr intake (g)	F_m ($d\ l^{-1}$)	Daily Ca +Sr intake (g)	F_m ($d\ l^{-1}$)
Low Ca only (0.25%)	4.9	0.017	45	0.0014
High Ca only (1.7%)	36.0	0.074	281	0.00041
Low Ca + high Sr (0.25% Ca + 3% Sr)	105.8	0.077	693	0.012

In goats the increased dietary strontium had a similar effect to that of the high calcium diet. In contrast in cows the increased dietary strontium had no significant effect compared with that for the low calcium alone diet. The authors concluded that there was no advantage to be gained in using stable strontium in preference to stable calcium.

The effect of stable strontium dosing at low levels of Ca intake has recently been investigated in lactating goats (Hove & Hansen 1994). Twelve goats were each given 3.8 g d^{-1}, equivalent to half the recommended daily Ca intake and divided into three groups receiving 20 mg d^{-1}, 350 mg d^{-1} or 1670 mg d^{-1} of stable Sr. Increased levels of Sr intake had no effect on the relative transfer of ^{85}Sr to milk in these conditions.

iii) Barium sulphate

The potential effectiveness of barium sulphate in reducing radiostrontium transfer to bone in rats has been studied by Volf (Volf 1960; 1961; 1964; Volf & Roth 1966) and Borisov & Krivchenkova (1964). The studies by Volf showed that the effectiveness of various forms of barium sulphate in reducing ^{85}Sr deposition in bone differed substantially, but always increased considerably, in the presence of soluble sulphates, giving a maximum reduction factor of 3.9. In agreement with other studies at least twice as much ^{85}Sr was absorbed in fasting rats compared with fed animals. However, barium sulphate in fed animals decreased the retention of ^{85}Sr only in combination with sodium sulphate.

In the absence of studies with lactating animals, and considering the differences observed with barium sulphate prepared using different methods, considerably more work would be needed before the use of barium sulphate could be considered as a potential countermeasure for radiostrontium transfer to milk.

iv) Clay minerals

A variety of different clay minerals have been tested as potential strontium binders, and some of the results appear to be rather contradictory.

Various *in-vitro* tests have been conducted to test the potential effectiveness of clays as binding agents. Two bentonites (a sodium and calcium montmorillonite both with high cation exchange capacity (CEC)) and one Kaolin (with a low CEC) were tested in artificial rumen fluid by Barth & Bruckner (1969) and found to have no binding effect. Preliminary studies by Hazzard (1969) also suggested that non-activated verxite would not be very effective in reducing radiostrontium uptake. Hansard (1964) found that ^{89}Sr binding by activated verxite (a refined vermiculite) in *in-vitro* tests varied from 58-84% in solutions of NaCl, NaOH, KOH and distilled water, but binding was 35% or less in rumen, stomach or small intestine juices. Nevertheless, *in-vivo* tests with the activated verxite, at 5% or 10% of the diet, showed a clear reduction of about 1.5 fold in ^{89}Sr blood levels after a single oral dose of ^{89}Sr to yearling wether lambs, with excretion in faeces from orally contaminated lambs increasing from 72% to 84%. In contrast, vermiculite, fed at 3% of the diet to dairy goats (equivalent to 50 g d^{-1}), showed little effect in reducing ^{85}Sr secretion in milk, urine or faeces (Hazzard 1969). Similarly, no significant reduction was observed in ^{85}Sr levels in pigs fed local mineral clays at 1% of the diet (Mirna 1970).

Recently the potential effectiveness of a range of synthetic clay minerals in reducing radiostrontium levels in milk has been tested in dairy goats by Hansen et al. (in press). Lactating goats were given ^{85}Sr prior to treatment with clays and then the reduction achieved by dosing with the clays over a 14 d period was measured. Five different types of zeolite were tested and a mordenite, the zeolites were all Zeolite A, but with different cations (Na, K, Ca, Mg or Na). For Zeolite A(Na) a mean reduction of ^{85}Sr in milk of <25% for 1-4 g d^{-1} increased to 38% for 10 - 30 g d^{-1}, equivalent to a reduction factor of 1.6. This represents a rate of dosing of about 0.5 g kg^{-1} liveweight which is a comparatively large amount and at the limit of voluntary intake. The authors concluded that the tested compounds were not suitable radiostrontium binders.

The potential use of modified smectites (pillared layered clays - PILCs) has also been considered recently. The smectites used had been modified so that the spacing between interlayer lattices was appropriately sized to be able to trap the ^{85}Sr ion. An initial experiment with lactating goats orally given ^{85}Sr and 10-30 g PILCs for two weeks was unsuccessful, since no appreciable reduction in ^{85}Sr content of milk was achieved. Although the PILCs are able to trap and retain strontium, *in-vitro* tests have shown that this process is rather slow, and probably does not occur rapidly enough to be effective during passage through the ruminant gut (Assimakopoulos et al. 1994).

v) Alginates

Sodium alginate is extracted from certain varieties of brown algae and is known to have a higher binding affinity for strontium than for calcium (Haug 1961). The affinity depends on the form of alginate, which in turn depends on the seaweed from which it is extracted. Sodium alginate from Laminaria hyperborea stems was reported to have a decreasing affinity for the following divalent ions, in the order Sr>Cd>Ca (Haug & Larson 1964). The relative affinity for Sr compared with Cd (and possibly Ca) depends on the ratio of mannuronic acid to guluronic acid in the alginate source. The lower this ratio the higher the affinity for Sr with respect to Cd (Haug & Larson 1964). Alginates are tasteless and odourless and are therefore potentially useful selective strontium binding agents to reduce radiostrontium absorption in the gut.

Reduction of radiostrontium levels in animals by the administration of alginates has been reported for a variety of animals including rats (Waldron-Edward et al. 1965), piglets (Van der Borght et al. 1967), humans (Hesp & Ramsbottom 1967) and dairy cows (Lengemann et al. 1974). This effect has been shown to be due to reduced absorption in the gut in rats (Skoryna et al. 1964; Moor & Elder 1965).

The relative timing of administration and contamination affects the reduction achieved. In humans, Hesp & Ramsbottom (1965) reported a reduction factor of 9, 19 and 3 when sodium alginate was administered 20 min before, 2 min before and 20 min after dosing respectively with ^{85}Sr. Similarly Paul et al. (1964) showed that the maximum effectiveness in rats occurred when both radiostrontium and sodium alginate were administered simultaneously; administration 30 min before, simultaneously and 30 min after a pulse dose resulted in reduction factors in bone of 1.8, >3 and 1.5 respectively. When rats were fed continuously at 10%, 20% and 30% of the diet reduction factors after 24 h of 1.7, 2.7 and 3.6 were achieved. Rats were fed continuously for 5 d prior to ^{89}Sr dosing on the treatment diets and those on the 20% and 30% diets failed to gain weight and became constipated.

In piglets, given a pulse dose of ^{85}Sr in milk with 5% sodium alginate, a reduction factor of 6.7 for ^{85}Sr in the whole body was achieved over 29 d by Van den Borght et al. (1967). Furthermore, accelerated biological half-lives were reported, of 0.9 d for the first component in alginate treated piglets compared with 1.5 d for controls, and 24 d for alginate treated compared with 36 d for controls for the second component. Because Ca absorption was not affected the OR for the whole body was reduced from 0.27 to 0.065. Even at a level of 5% alginate in the milk diet piglets found the milk to be unpalatable (Van den Borght et al. 1967).

In dairy cows, reduction factors of 3.3 - 5 were achieved in milk when sodium alginate, derived from Laminaria species, was incorporated at 5 - 7% of the diet of dairy cows (Thompson et al. 1971; Lengemann et al. 1974). However, the addition of alginate to the ration affected palatability. Most cows rejected alginate doses above 5 - 7% of the diet, and some rejected doses as low as 1%.

The addition of alginate has been found to have no detrimental effect on the absorption of Ca or on body retention of Ca in man (Carr et al. 1968; Sutton et al. 1971) and other animals (Van den Borght et al. 1967).

Calcium alginate is apparently as effective as sodium alginate in reducing absorption of strontium, barium and radium, and has the added advantage of being insoluble in water, which would overcome the disadvantage of high viscosity. Calcium alginate can be extracted from Macrocystis pyrifera, and can readily be supplied in powdered form, and constitutes a potentially useful and better alternative to sodium alginate. In rats given calcium alginate, at 15% by weight of the diet, a reduction of 10 fold was achieved in whole body ^{85}Sr contamination (Kostial et al. 1981). No adverse effects were noted in bone physiological characteristics or histopathology, or in Zn or Mn levels. However, levels of Fe were reduced by 20% and haemoglobin values were slightly lower in the treated animals. It is not possible to state that this was due to the calcium alginate as the rats were also given iron(III)ferrocyanide and potassium iodide, although the authors felt this was probably due to the alginate, as inhibition of iron absorption by sodium alginate has been observed in studies with man (Hodgkinson et al. 1967) and rats (Wöbling et al. 1980). Hodgkinson et al. (1967) observed that the affinity of sodium alginate for different ions, probably involving an ion-exchange mechanism, varied in the order Fe>Sr>Ca>Mg, and that binding was dependent on pH, being virtually abolished below pH 3.0. However, contrasting results were reported by Harrison (1968) in an experiment where alginate was added to the diet of rats at 10% of the diet for a period of one year and there were no changes on growth and body weights, or in Ca, Na, K, Mg or Fe concentrations .

The limited data available for dairy cows would suggest that good reduction factors can be achieved using sodium alginate. However, the use of sodium alginates would not be advisable because of the difficulty of making it palatable to dairy animals so that dosing could be carried at sufficiently high dose rates to be reasonably effective. Unfortunately, currently no dairy animal dosing experiments with calcium alginate have been reported, to the authors knowledge, so its effectiveness would need to be tested. In addition the potential effect of calcium alginate on iron absorption and the palatability of calcium alginate to ruminants would need to be evaluated.

One further aspect of alginate dosing needs to be considered. Since alginates would provide a carbohydrate source to ruminants the microbial flora of the gut would probably adapt with time to be able to digest the alginate and provide an additional carbon source for the animal. Therefore the long-term effectiveness of alginates may alter. Thus experiments with calcium alginate and dairy animals would need to be long enough to test the effect of microbial adaptation.

vi) Organic compounds

Few studies have considered the potential use of organic compounds in reducing radiostrontium transfer to milk. The addition of animal oils or vegetable oils to the diet of rats, or varying the protein content (both by increasing and decreasing), was reported by Annenkov (1964a) to slightly reduce gut absorption and thereby ^{90}Sr deposition in bone.

vii) Other substances

A variety of different compounds which are known to react or compete with Ca or Sr have been tested in lactating cows and goats by Comar et al. (1966b). The additives used were:

(i) NaEDTA at 300 g d^{-1} in cows and 30 g d^{-1} in goats

(ii) K-hydrogenphosphate at 130 g d^{-1} in cows and 48 g d^{-1} in goats

(iii) DOWEX 50 ion exchange resin at 300 g d^{-1} in cows and 100 g d^{-1} in goats

(iv) Mg-sulphate at 68 g d^{-1} in cows and 38 g d^{-1} in goats

For the first three compounds a slight increase in radiostrontium transfer to milk occurred; Mg-sulphate caused a slight decrease. The NaEDTA caused a slight increase in the $OR_{milk/diet}$ value whereas the other substances did not. Subcutaneous injections of parathormone caused slight decreases in milk radiostrontium, and the effect was reversed by cortisone. In goats, both treatments caused an increase in the $OR_{milk/diet}$, but this did not occur in cows. Calcium gluconate, NH_4Cl, NaEDTA and CaEDTA were also administered by continuous intravenous infusion for up to 200 h. At the levels used, calcium gluconate caused a 2 fold reduction in the ^{85}Sr level in milk; NH_4Cl had no effect and the EDTA salts caused an increase.

Recently, a potential radiostrontium binder has been developed in Belarus, which is composed of chemically modified crumbled wood. *In-vitro* binding tests in Belarus have shown a 50% reduction when using 50 ml of water containing stable Na, K, Ca and Mg. Independent tests of the binder have been carried out in Norway , and the *in-vitro* binding capacity in rumen fluid has been compared with that of Zeolite A(Na) (Hansen et al. 1994). Two different samples of the binder (BIAR1 and BIAR2) were tested. The effect in reducing the content of ^{85}Sr in the supernatant was similar for Zeolite A(Na) and BIAR1, with a maximum removal of 98% for both when the BIAR1 was present at 0.5^{-1}g in 100 ml fluid. However, the equivalent value for the second batch of binder, BIAR2, was 60% lower. The BIAR binders were therefore potentially as effective as the Zeolite A(Na) but not sufficiently effective, on a weight basis, to be considered useful for practical application.

3.4 FOOD PROCESSING

One potentially effective countermeasure for radiostrontium contamination is the decontamination of contaminated milk using ion-exchange resins (McHenri et al. 1991; IAEA 1994b). Radioiodine, radiocaesium and radiostrontium can all be removed from milk with a high efficiency (> 90%) using appropriate resins, although palatability and nutritional value may be affected.

The fraction of radiostrontium retained in the different milk products varies. Food processing retention factors for radiostrontium are given in Table 3.10, together with the processing efficiency based on information published by the IAEA (1994). The food processing retention factor, Fr, is defined as the total amount of a radionuclide in processed food divided by the total amount of the radionuclide in the raw food (Bq processed/Bq raw). The processing efficiency, P_e, is the ratio between prepared food and raw product weights (kg prepared food/ kg raw product). Hence, F_r in Table 3.10 is the fraction of radiostrontium which is retained in food after processing. For dairy products the yield of the product is important and therefore the processing efficiency is also given.

Table 3.10 Food processing retention factors, F_r, and processing efficiencies, P_e, for radiostrontium in dairy products (IAEA 1994b).

Product	F_r		P_e	
	expected values	range	expected values	range
Cream	0.07	0.04-0.25	0.08	0.03-0.24
Skimmed milk	0.93	0.75-0.96	0.92	0.76-0.97
Butter	0.006	0.0025-0.012	0.04	0.03-0.05
Buttermilk	0.06	0.03-0.07	0.04	0.03-0.14
Butterfat		0.001-0.002	0.04	0.04-0.04
Milk powder		1.00		0.12
Cheese				
goat		0.61	0.12	0.08-0.17
cow rennet		0.025-0.80	0.12	0.08-0.18
cow acid		0.04-0.08	0.10	0.08-0.12
Cottage cheese- rennet		0.07-0.17		
Cottage cheese- acid		0.22		
Whey				
rennet		0.20-0.80	0.90	0.70-0.94
acid		0.70-0.90		0.82
Casein				
rennet		0.10-0.85		0.03-0.06
acid		0.05-0.08		0.01-0.06
Casein whey				
rennet		0.08-0.16	0.76	0.73-0.79
acid		0.67-0.86	0.78	0.75-0.79
Milk - ion exchange	0.1			

In calculating the concentration of radiostrontium in the dairy product both F_r and P_e need to be considered. For instance, the F_r value of 0.61 for goat cheese relates to a 12% yield. Therefore, 39% of the radiostrontium is removed by the conversion to goat cheese, but, owing to the 12% yield of cheese, the activity concentration of radiostrontium in goat cheese is 0.61/0.12 = 5 times that of goat milk.

Although processing milk to selected dairy products with lower radiostrontium levels is possible the contaminated milk may not be accepted by commercial concerns, and therefore it would be unwise to rely on this approach.

3.5 COUNTERMEASURE SUMMARY

A variety of different options are available for reducing radiostrontium to milk, and a proposed strategy for selecting appropriate countermeasures is given in Fig. 3.1. Potentially effective countermeasures which would need further work, in order to implement in the event of an accident are included.

Figure 3.1 A simplified strategy to assist in the selection of suitable methods of reducing radiostrontium levels in milk.

4 THE UK DAIRY FARMING INDUSTRY

4.1 CATTLE

In June 1993 there were approximately 2 665 000 dairy cattle in the UK. England supported the majority of these with 1 861000, Wales had 304 000, Scotland 231 000 and Northern Ireland 269 000 (MAFF 1993a). These numbers had reduced by 18% since 1986 probably because of the introduction of milk quotas.

Dairy cows are generally outside from mid-March to mid-November dependent upon the amount of rainfall in a particular area and its soil type. They are housed throughout the winter months and fed mainly grass silage. Some areas in the south east, because of its better climate, feed a mixture of maize silage and grass silage. Hay is only occasionally fed due to problems drying it adequately in the UK; silage is also preferred as it has a higher feed value. In some areas the cows are housed at night in June and July and fed silage and concentrates to boost their milk yield and so take advantage of the better seasonal milk prices available.

In 1993, 12.9% of the agricultural land in England was devoted to dairying, 15% of Wales, 3.6% in Scotland and 24.3% in Northern Ireland (MAFF 1993a). Of this area 55% of the forage area is grazed and 45% cut for silage or hay. There are usually 2 cuts for silage, the first in May and the second in June. Hay is usually cut in June. The harvesting time of both is dependent on weather and location.

The average milk yield per cow in the UK, per lactation, is 5350 l (Nix 1990). To achieve this level of production each cow consumes, on average, approximately 2 tonnes of hay (or equivalent) per year (Nix 1990). To supplement this, an average of 0.3kg of concentrates is fed per litre of milk. This concentrate ration would include mainly by-products of wheat and barley refining, molasses and a mineral/vitamin mix, and have a protein level of approximately 16% (Carrs Agriculture pers. comm.).

Of a total volume of 13 322 million litres of milk in 1992/93 the amounts processed to different dairy products was (MAFF 1993b):

Liquid milk	49.7%	Butter	15.5 %
Cheese	22.1 %	Condensed Milk	3.5 %
Cream	3.6 %	Whole milk powder	4 %
Other	1.6 %		

The Statutory Milk Marketing Scheme came to an end on 1st November 1994. Milk producers are now free to sell milk as they wish, and dairy companies can buy direct from the producers.

4.2 GOATS

There are approximately 50,000 dairy goats in the UK (Mowlem 1990) the average herd size is 50 goats, each producing on average 800 litres of milk per 300 day lactation (Nix 1990). A value of 1060 l y^{-1} was calculated using the results of an ITE survey into the current agricultural and commercial practices of the dairy goat industry in the UK conducted in March 1991 (Mayes et al. 1992; Barnett & Beresford 1993). To obtain the information required for the above survey, 2500 questionnaires were circulated with the March copy of the British Goat Society magazine to the keepers of dairy goats. The replies received represented approximately 10% of the estimated UK dairy goats. For the purposes of our study we allotted the replies to one of three categories depending on the number of milking goats :

Small scale producers	<5
Medium scale producers	6-20
Large scale producers	>20

We identified three different grazing regimes:

a. Permanently housed with no access to pasture
b. Access to pasture throughout the year (generally only during the day)
c. Access to pasture during the summer months but housed during winter

The larger herds are generally housed indoors all year and normally fed hay to avoid milk taints, worms and fencing problems. Most small herds have permanent access to pasture, usually in the daytime only and limited a little more in winter. Table 4.1 shows the annual volume of milk produced under different grazing regimes in 1991.

Table 4.1 The annual volume of milk produced under different grazing regimes in 1991.

Grazing Regime	*Small*	*Medium*	*Large*
		Farm size	
		Milk produced (kl)	
Permanently housed	261	327	1460
Permanent access to grazing	375	610	259
Grazing summer/ housed winter			
summer production	126	281	677
winter production	106	237	572

The diet of dairy goats outdoors is varied, they generally select against grasses, preferring species such as thistles, nettles and Rumex spp.. When housed, they are fed approximately 0.8 kg DM of long fibre forage (hay, straw etc.) and 0.73 kg DM concentrate per litre of milk of milk produced (Nix 1990).

The sales outlets vary according to the size of the herd, 50% of the milk produced from the larger herds is sold directly to supermarkets or dairies whereas, the largest outlet for milk from the small herds is consumption by the household. Figure 4.1 shows a comparison of the outlets for milk from the different herd size categories (Barnett & Beresford 1993).

As a total of all the milk produced, 19% went to dairies, 8% each to the household, supermarkets and other shops, 6% sold at the farm gate and 2% as animal feed.

Since the majority of the milk produced by the large producers is sold direct to supermarkets and dairies it is probable that most goat milk and milk products consumed by the general public will have come from housed animals. Goat keepers will probably consume more dairy goat products than the general population. Also, for the smaller producers home produced goat milk is their usual source of dairy produce and the majority of this milk will have come from goats with access to pasture. The pastures used for the smaller herds are likely to be less improved and may therefore result in higher transfer of radionuclides.

In general there has been an increase in the sale of goat milk products noted by supermarkets in more recent years (Mowlem 1990). A considerable proportion of all the goat milk sold in the UK may be consumed by people who are allergic to the proteins in cows milk and many of this group are infants.

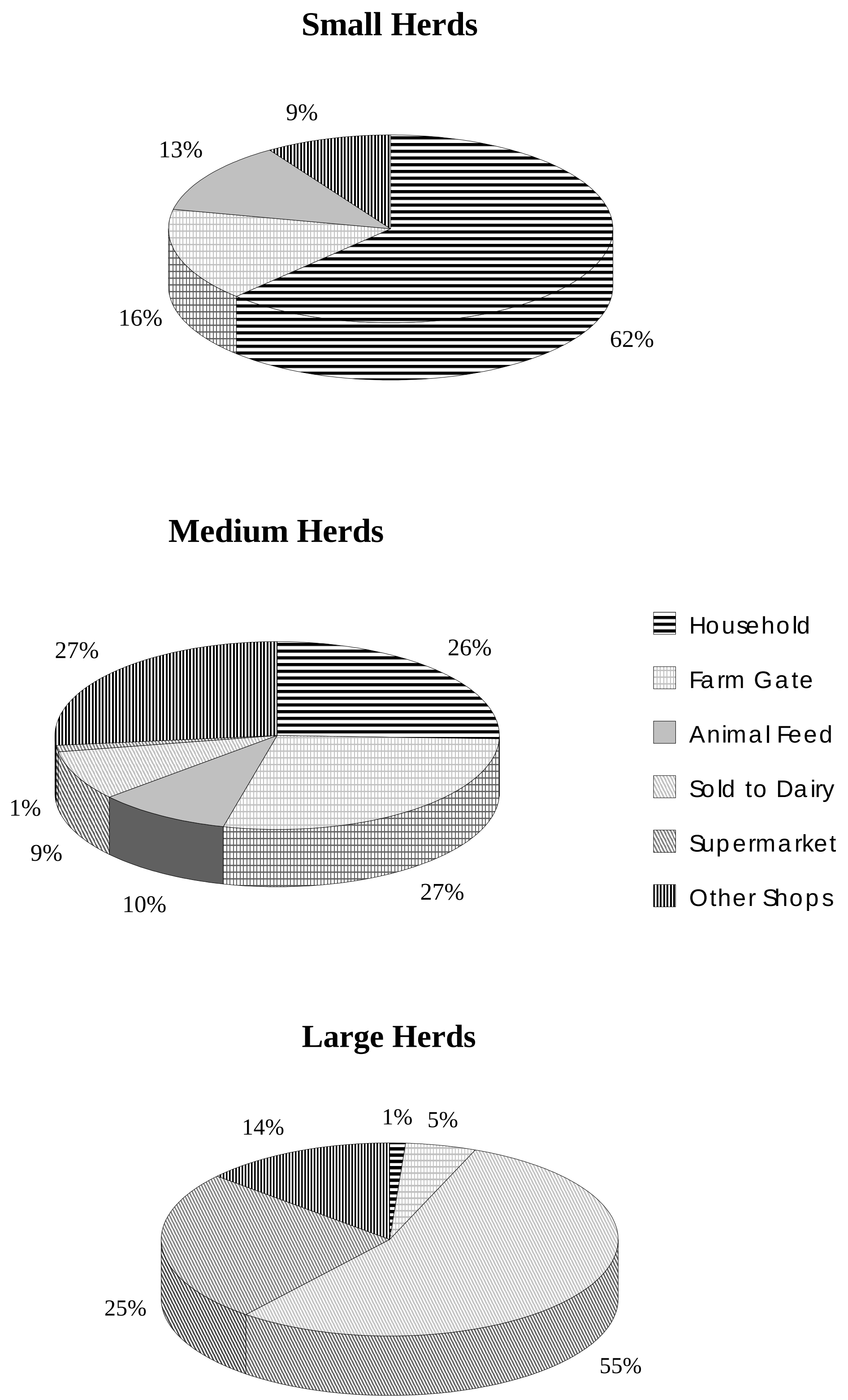

Figure 4.1. A comparison of the outlets for milk from the different herd size categories (from Barnett and Beresford 1993).

4.3 SHEEP

The average milk yield of British milksheep and East Freisland ewes (ie. commercial dairy sheep) is approximately 300 litres (Nix 1990).

At present most production is small scale and little liquid milk is sold for human consumption, most is processed into yoghurt and cheese. Producers have to find their own outlets although some deliver direct to cheesemakers. The market prospects are at present limited, but appear to be expanding (Nix 1990).

5 CONCLUSIONS

- Contamination of milk by ^{90}Sr constitutes a potentially important component of the collective dose to the population after a nuclear accident. Therefore it is important to have effective, practical countermeasures available to prevent or reduce radiostrontium contamination of milk.

- The transfer of radiostrontium to milk is highly dependent on the calcium intake and status of the ruminant. Levels of radiostrontium in milk respond rapidly to those in the diet. When dairy animals are on normal dietary calcium intakes the transfer of radiostrontium to milk is likely to be inversely proportional to that of the dietary calcium intake. Calcium is homeostatically controlled with constant levels in milk and the transfer of radiostrontium to milk is dependent on Ca intake. Therefore, the usefulness of conventional transfer coefficients for radiostrontium is limited, because of the dependence on calcium metabolism.

- A relationship was noted between calcium intake and radiostrontium transfer to milk, which might allow improved estimation of radiostrontium transfer to milk.

- The simplest and most effective countermeasure is to provide dairy animals with uncontaminated feed. If supplies of uncontaminated feed are limited, dairy animals should be given priority for this feed, in preference to animals reared for meat. This countermeasure has the added advantage that it will be effective for other radionuclides which may be present in the fallout.

- If the affected area is very large or deposition occurs in late spring it will be more difficult to supply uncontaminated fodder to large numbers of dairy cows and the use of compounds to limit milk contamination will need to be considered. The most practical and simple method of doing this would be to apply lime to contaminated soils. However, the potential effectiveness of liming will depend on the prevailing calcium status of the soil, and since most UK agricultural soils are not deficient in calcium the effect of liming may not be high. On organic soils liming may increase radiostrontium uptake by plants, and therefore the effect for each major organic soil category would need to be checked before application. The application of organic matter, as an alternative to lime, may also be effective, but the concomitant effect on radiocaesium if present, would need to be tested.

- If there is widespread high deposition of radiostrontium then surface, or preferably skim and burial ploughing or the use of turf harvesters should be considered. Such radical methods, which would remove land from immediate forage or grass production, would need to be carefully managed so that supplies of adequate amounts of animal feedstuffs were maintained. Surface ploughing would be possible immediately, however, skim and burial ploughing would be a preferred option and would not be possible in the short term since such ploughs would need to be imported from Denmark, or manufactured in the UK.

- Stable calcium administration is a practically feasible option since increasing calcium intake by a factor of two would probably decrease radiostrontium levels in milk by a concomitant amount. Relatively small additional doses of stable calcium are unlikely to be effective, and daily Ca intake would ideally need to be increased by 2-3 fold over the normal Ca intake of the dairy animals. An alternative approach is to change the diet to herbage with naturally high calcium contents, such as lucerne, but this approach would need to be studied further for the UK farming situation.
- The use of additives given to ruminants to reduce radiostrontium absorption and hence transfer to milk is an alternative countermeasure which should be considered, particularly if difficulties are encountered with supplying uncontaminated feedstuffs for dairy animals. Countermeasures based on dosing animals with additives are easy to administer for dairy animals, which are routinely handled twice daily, and potentially more cost-effective than soil-based treatments. Few alternative compounds are available which could be given to ruminants to reduce the transfer to radiostrontium to milk. Currently tested substances are either of limited effectiveness (e.g. Zeolite A(Na)) or need further investigation (e.g. calcium alginate) before they could be considered as a practically feasible option which would be equally or more effective than stable calcium
- Alternatively another effective response is to process the milk to reduce radiostrontium levels, but it is probably socially more acceptable to apply countermeasure to the animal than to the product. Processing milk, by ion-exchange or production of milk products, may not be possible if contaminated milk is not accepted by commercial companies.
- A summary of preferred countermeasures has been provided in the form of a flow diagram, which will help to identify suitable strategies for applying countermeasures in the event of radiostrontium deposition.

6 RECOMMENDATIONS

Soil-based countermeasures are potentially effective in reducing radiostrontium levels in pasture grass and fodder. It would be helpful to have additional information on the response to liming and organic matter application of the major soil types in agricultural land in the UK which are used for dairy farming.

Other techniques developed in the last decade for removing the contaminated top soil, should be considered for testing in UK conditions; in particular skim and burial ploughing is a potentially useful countermeasure technique.

In circumstances where radiostrontium contamination has occurred on a large scale, and particularly when this occurs in spring when availability of forage may be restricted, the use of additives or binders is a potentially important and practically acceptable countermeasure to reduce radiostrontium levels in milk. Furthermore, the general strategy of reducing contamination at this stage is potentially one of the more cost-effective and acceptable countermeasure strategies available. Currently, although the administration of stable calcium is practically possible it has limited effectiveness, at feasible dose rates, for cows on an adequate calcium diet. Highly effective, specific radiostrontium binders (equivalent to AFCF for radiocaesium) have not been identified or tested in dairy animals, although some substances deserve consideration, including calcium alginate and possibly barium sulphate and various types of clay minerals. If these substances were to be tested factors such as the dose response, effect of the comparative timing of contamination and treatment, potential transfer of the compounds into milk and the possible side effects when ingested by humans would all need to be considered.

It is highly probable that more than one radioisotope which is readily transferred to milk would be emitted in the event of a nuclear accident. Given the considerable advantages, in terms of practicality and acceptability, of using animal dosing techniques to reduce radionuclide contamination the development of a multiple-substance countermeasure, which would be able to effectively reduce the transfer of radiocaesium, radiostrontium and radioiodine, would seem to merit consideration. Such a device would need to contain effective binders or competitors for all three isotopes. The effectiveness of AFCF and potassium iodide have been established; that of a suitable effective substance for reducing radiostrontium transfer to milk still needs development and testing. Potentially effective substances, such as calcium alginate, have been identified which merit further study.

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9. BIBLIOGRAPHY

There is a large amount of information available in the scientific literature on the radioecology of radiostrontium, covering basic metabolism, environmental behaviour, rates of transfer to tissues and milk and many other associated subjects. Comparatively few of these papers and reports have been directly referred to during the preparation of this report. However, during the selection of the most relevant literature many papers were acquired and read. These have been listed in the accompanying bibliography, using both an author and subject index. In the subject index a precise of some of the papers is also provided. The bibliography will continue to be updated and revised in future. Hard copies of the bibliography are available, and also floppy discs with the file, with which rapid searches could be carried out for particular subjects areas of interest.