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FEASIBILITY OF AN ON-LINE FISSION-GAS-LEAK DETECTION SYSTEM

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16. Abstract

Calculations were made to determine if a cladding failure could be detected in a 100-kW zirconium hydride reactor primary system by monitoring the highly radioactive NaK coolant for the presence of I^{131}. The system is to be completely sealed. A leak of 0.01 percent from a single fuel pin was postulated. The 0.364-MeV γ of I^{131} could be monitored on an almost continuous basis, while its presence could be verified by using a longer counting time for the 0.638-MeV γ. A lithium-drifted germanium detector would eliminate radioactive corrosion product interference that could occur with a sodium iodide scintillation detector.

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SUMMARY

The feasibility of an on-line fission-gas-leak detection system was studied for a 100-kilowatt zirconium hydride reactor. To be considered effective, the system must detect some fission product within the highly radioactive sodium potassium (NaK) coolant in a completely sealed loop. A proposal for accomplishing this includes a bypass in the primary loop in which a sample may be retained (frozen) to improve the fission product activity with respect to background.

The fission product iodine-131 (I^{131}) was chosen for its 8-day half-life, fairly energetic γ ray (0.364 MeV), high fission yield (2.9 percent), and high γ fraction (84.9 percent).

The background (NaK) activity at equilibrium was estimated to be 3.79×10^{10} dis/sec/kg of NaK, and after decaying 8 days to be 4.0×10^{6} dis/sec/kg NaK.

The activity of I^{131} per kilogram of NaK, assuming a 0.01-percent release from a single pin, is 1.76×10^{6} dis/sec at equilibrium and 8.8×10^{5} dis/sec after 8 days. Activity within the 0.08-MeV peak width of two I^{131} gamma-ray energies was calculated for a 7.6- by 7.6-centimeter (3- by 3-in.) sodium iodide (NaI) detector. Background and I^{131} activities (dis/sec) were 2.48×10^{10} (background), 1.1×10^{6} (0.364-MeV γ), and 6.7×10^{4} (0.638-MeV γ) at equilibrium and 3.33×10^{6}, 5.6×10^{5}, and 3.4×10^{4}, respectively, after 8 days.

These numbers were translated into the counting time necessary to assure the presence of I^{131}. Counting times are 2 seconds for the 0.364-MeV γ at equilibrium and 10 minutes for the 0.638-MeV γ. A counting efficiency of 5 percent was assumed. It was concluded that a lithium-germanium detector would be best for the detection of a fission product leak. Both this type of detector and the 7.6- by 7.6-centimeter (3- by 3-in.) NaI detector could detect the postulated leak on an essentially continuous basis. However, the lithium-germanium detector can improve resolution by a factor of 10 or more, thereby eliminating interference from activated corrosion products.

INTRODUCTION

The zirconium hydride nuclear reactor is being developed for use with a space-electric power system. The fuel contains sufficient hydrogen to make the neutron flux spectrum slightly epithermal. It is contained in a glass-lined Hastelloy cladding. The coolant is liquid sodium potassium (NaK) circulating in a closed loop that is maintained completely full at all times for operation in a zero-gravity environment. The study reported in this memorandum was made to determine the feasibility of detecting a cladding failure in the prototype ground test by means of monitoring the coolant for released fission products. Since the coolant loop is maintained full of liquid at all times, there is no chance of separating gaseous fission products, which could then be measured away from the highly radioactive coolant.

A fuel-element failure can occur whenever there is a break in the Hastelloy cladding. The glass liner which cuts down on hydrogen (H_2) diffusion will probably already be cracked and the mobile fission products will move through these cracks and into the coolant through the break in the cladding. It may be possible to measure the activity of some fission product against the intense background of the coolant either on a continuous basis or at intervals by allowing the background to decay faster than the selected fission product. One way of accomplishing this would be to have a small bypass line in the primary loop that could direct the coolant to a well-shielded area. At planned intervals the line would be frozen and the retained inventory allowed to decay for a predetermined length of time. The gamma activity would be scanned in the energy ranges of expected fission product activity. The frozen portion could then be reheated to allow flow in the bypass line.

PROPOSED SYSTEM

Figure 1 is a schematic representation of the primary loop and the bypass diagnostic loop. A heavy gamma shield is needed to prevent interference from reactor gamma radiations. A neutron shield must be provided to protect the sensitive detection equipment. The electromagnetic (EM) pump in the bypass line is used to aid flow prior to sampling and to stop it during the freezing operation.

CHOICE OF FISSION PRODUCT ISOTOPE

The fission product chosen for detection should have the following properties:

(1) Long half-life relative to Na^{24} and K^{42} (of the order of a day or more): This will improve the isotopes relative activity over background with time.

(2) High activity throughout reactor life:

(a) A half-life of less than a few weeks will ensure that the maximum activity the isotope can achieve will be reached quickly and also that the decay rate will be high when it is being scanned.

(b) A high cumulative fission yield provides a large inventory for escape into the coolant.

(3) Volatility: This requires that the product be in a gaseous or vapor state at the fuel operating temperature so that it can move more freely to a failure site.

(4) High-energy gamma: The γ-ray emitted should be of sufficiently high energy (>0.2 MeV) to avoid the cluttered background of Na^{24} and K^{42} scattered gamma rays in that range.

(5) High yield: The yield of the gamma ray under observation should be high for ease of detection.

Selection of an isotope for observation was relatively simple. Of the volatile fission products, only iodine-131 (I^{131}), iodine-133 (I^{133}), and xenon-133 (Xe^{133}) have sufficiently long half-lives to improve their activity ratio with respect to Na^{24} and K^{42} after prolonged decay (ref. 1). However, Xe^{133} emits a relatively low-energy gamma-ray (0.1 MeV) which may easily be obscured in the low-energy scatter, particularly of K^{42}. Iodine-133, while it is produced in greater quantity than I^{131} by a factor of about 2.5, has only a 21-hour half-life compared to 8 days for I^{131}. Thus, in only about $1\frac{1}{2}$ days of decay the I^{131} activity will exceed and continue to exceed the I^{133} activity. Both produce about the same energy γ with the same frequency. Thus, the feasibility of this type of detection was based on the practicability of detecting I^{131} activity amid the activated NaK alloy background. It was assumed that any direct reactor background activity could be sufficiently shielded so as not to interfere with I^{131} detection.

FEASIBILITY CALCULATIONS

Sodium Potassium Background Activity

Calculation of the NaK activity has been done by Aerojet General (private communication) for the 600-kilowatt SNAP-8 zirconium hydride reactor. The equilibrium activity of the Na^{24} was 4.4 Ci/kg of NaK, and that of the K^{42} was 1.77 Ci/kg of NaK. For a 100-kilowatt reactor, these values reduce to 0.73 Ci/kg of NaK for Na^{24} and 0.294 Ci/kg of NaK for K^{42}. Sodium potassium activity was presumed to come from those two isotopes, which is a valid assumption for short-term decay (as long as several days) (ref. 1). The proposed thermal power in our applications is 100 kilowatts. Table I summarizes the activity of NaK from equilibrium through 8 days of decay.

Iodine-131 Activity

It was necessary to estimate the amount of I^{131} that might be present in the coolant in the event of a cladding failure. The total activity of I^{131} in the core at equilibrium is given by

$$A_{I^{131}} = 3.1\times10^{10}\ Py \qquad \text{(ref. 1)}$$

In this equation the reactor power P is 1×10^{5} watts and the fission product yield of I^{131} y is 0.029. The symbol A denotes the fission product activity in dis/sec.

Hence, the total I^{131} activity in the core is 9.0×10^{13} dis/sec. The following assumptions were then made:

(1) One out of the 85 fuel pins fails. The activity in each depends on location in the reactor. Conservatively, the pin with the lowest relative power was chosen as having failed. Its power relative to average power is 0.75. The activity available for release to the coolant is thus $9.0\times10^{13} \times \frac{1}{85} \times 0.75 = 7.93\times10^{11}$ dis/sec.

(2) One-hundredth (0.01) percent of the activity escapes from the pin and is distributed evenly throughout the NaK (7.93×10^{7} dis/sec distributed in the NaK).

(3) The activity of I^{131} per kilogram of NaK is 1.76×10^{6} dis/sec, assuming there are 45 kilograms (100 lbm) of NaK in the primary and diagnostic system at equilibrium.

The activity of I^{131} is compared to the NaK activity on a per-kilogram basis for various decay times in table II.

The question at this point is whether or not the I^{131} activity in the energy range of its primary decay γ (>0.36 MeV) can be detected through the NaK background in that same energy range. The first step would be to determine this background. It is necessary to introduce a particular detector since gammas of a wide spectrum of energies are produced within the detector itself. The choice made here was a 7.6- by 7.6-centimeter (3- by 3-in.) NaI detector.

In the 7.6- by 7.6-centimeter (3- by 3-in.) NaI detector the fraction of γ's absorbed (photofraction absorption) is 35 percent for the 1.37-MeV γ's (ref. 2) and 20 percent for the 2.75-MeV γ's from Na^{24}. Therefore, the scattered γ's account for 65 percent and 80 percent of the γ's, respectively. These give the continuous spectra behind the peaks, as shown in the typical spectrum analysis in figure 2.

The large peaks are the photofractions or unscattered γ's; the remainder represents primarily the Compton or scattered γ's.

Similarly, for K^{42} the photofraction of the 1.52-MeV γ is 32 percent and the Compton fraction 68 percent. Assuming that the distribution of the counts is uniform over the Compton range, the number of Compton counts per second per MeV can be calculated. The Compton counts occur over an energy range between zero and the maximum β

energy attainable from Compton scattering, which can be calculated from the following formula:

$$E_{\max \beta} = \frac{E_0}{1 + \frac{m_0 c^2}{2E_0}} \qquad \text{(ref. 3)}$$

where

$E_{\max \beta}$ maximum energy of dislodged β particle

E_0 energy of γ ray

$m_0 c^2$ rest mass of electron, 0.51 MeV

It is the β energy that is seen by the crystal.

The maximum β energy and resultant Compton background are summarized for the two Na^{24} γ's and the K^{42} γ in table III.

We may perform a similar analysis for the I^{131}, except that here we are interested in the photofraction (or the peak at 0.364 MeV), as well as in a second peak at 0.638 MeV. It is felt that simultaneous appearance of both peaks constitutes more positive identification of I^{131} in the coolant. In the case of the I^{131} γ rays, table IV summarizes the relevant data.

The width of the peaks for I^{131} is about 0.08 MeV for both the 0.364-MeV and 0.638-MeV γ's. The γ activity in those intervals produced by Compton scattering of radiations from the NaK is the counts per second per MeV from table III multiplied by 0.08 MeV. This amounts to 2.0×10^{10} counts/sec/kg of NaK. When these numbers are compared with the equilibrium activity of I^{131} in the range of the two γ-ray energies from table IV, it can be seen that it might be difficult to distinguish the photofraction peaks of I^{131} from the background if counting were attempted on a continuous basis. However, this prospect will be investigated further. The advantages of using freezing followed by a decay period can be seen from table V. The table shows that the I^{131} counts can become comparable to or even exceed the background level after several days of decay. The numbers for counts per second all assume a 100-percent counting efficiency.

Counting Time

Now that the expected counts from the contributing sources have been determined, it is necessary to estimate the counting time that would be required for adequate statis-

tics. Adequate statistics is defined for these purposes as that activity of an isotope which will yield $10\sqrt{N}$ counts, where N is the number of background counts and the $\sqrt{N}$ represents one standard deviation. In terms of the individual count rates, C_1 (I^{131} activity) and C_2 (background activity), the required time of counting works out to $t_c = 10^2/C_2(C_2/C_1)^2$. The ratio C_2/C_1 can be obtained from table V, but C_2 depends on the efficiency of the source-detector geometry. An efficiency of about 5 percent would be obtained for a point-source-to-detector distance of 6 centimeters (ref. 4). Let us assume that this efficiency is obtainable with a 1-kilogram sample by some relation of source to detector geometry. Hence, C_2 would equal 0.05 of the total NaK activities of table V. Table VI shows counting time as a function of days of decay. It can be seen that a 0.01-percent I^{131} release would be detectable in a reasonable amount of counting time for the 0.364-MeV γ even at equilibrium and in only 3 days of decay for the 0.638-MeV γ, where the necessary counting time would be 32 seconds. This latter γ could also be detected in only 10 minutes of counting time at equilibrium.

DISCUSSION

A premise for this feasibility study was that it may be necessary to retain (by freezing) a sample of the primary loop liquid metal (NaK) to allow favorable relative decay of the fission product with respect to the coolant in order to detect a fission leak. For this reason also a fission product with a long half-life relative to Na^{24} and K^{42} was selected. As it turned out, I^{131} with an 8-day half-life was capable of being detected if as much as 0.01 percent was released from a single fuel pin from either reactor. This could be done with as little counting time as 2 seconds even at equilibrium radiation levels. Hence, it is possible to count the 0.364-MeV γ of I^{131} on a continuous basis. A counter timer set every few seconds could yield a plot of any drifts in the background level as well as continually monitor for an abrupt change that would indicate a fission leak. A second channel could be tabulating counts in the 0.638-MeV range every 10 minutes to look for that particular I^{131} emission as confirmation.

Thus, it appears that sample retention is not necessary for detection of this magnitude of failure. However, it may be desirable in any event to have the capability of detecting failures of even smaller magnitude than a 0.01-percent leak. Since it has been shown that it is possible to continuously monitor for I^{131} (8-day half-life), it should be possible to monitor for a fission product with a higher fission yield which would have a higher specific activity. Such isotopes as I^{132} (2.4-hr half-life, 4.7 percent fission yield), I^{134} (52.5-min half-life, 6.7 percent fission yield), and Xe^{135} (9.13-hr half-life, 6.5 percent fission yield) would have higher specific activities and be detectable during fission gas leaks smaller than 0.01 percent. For example, since the equilibrium activity of I^{134} is some 2.3 times that of I^{131}, it would be possible to detect a 0.0042-

percent leak of this isotope in 2 seconds of counting. Of course, this depends on the energies of the radiations and the decay schemes of the isotope.

Although it appears possible to detect fission product releases of very small magnitude, the problem of interference arises - interference not from the general background radiation, but from corrosion products that may be released to the NaK coolant. If any of these products produce radiations within the I^{131} peaks, their presence might be interpreted as a cladding failure. As has been stated, confirmation of the presence of I^{131} could be obtained by the simultaneous observation of a second emission at a different energy. This would be true for any fission product isotope.

The ambiguity of the single determination can be demonstrated by reference to some of the isotopes that may interfere with readings in the range of the 0.364-MeV γ of I^{131} peak, that is, between 0.33 and 0.41 MeV (0.08-MeV width). Some isotopes with γ's in the range 0.33 to 0.41 MeV (ref. 5) are given in table VII. Even with the second measurement at the higher γ energy, confusion may still occur from the appearance of chromium-51 (Cr^{51}) with a 0.65-MeV γ since this may be a corrosion product from the piping along with iron-53 (Fe^{53}).

The possibilities of impurities interfering with positive identification of I^{131}, rather than any interference from a high background, is considered the primary problem. The significance of the problem can be somewhat modified by use of a detector with a higher resolution capability. Lithium-drifted germanium detectors offer peak bandwidths in the neighborhood of 6 keV (0.006 MeV) compared to the 80 keV (0.08 MeV) of the NaI detectors. This means the range of interference would be from 0.361 to 0.367 MeV, compared to the wider range discussed previously. Hence, none of the isotopes listed in table VII would interfere with the identification of the 0.364-MeV γ of I^{131}. The difficulty with these detectors, however, is that their efficiency is much lower, which may hamper the counting statistics. Hence, background counts would be reduced because of the narrower resolution, but so would the total counts from both I^{131} and background because of reduced efficiencies. An efficiency of 5 percent of that of a NaI detector is possible with lithium-germanium detectors. Background counts are additionally reduced by the amount 0.006 MeV/0.080 MeV because of the better resolution. It is possible to calculate, similar to the results of table VI, the counting time necessary with these detectors to obtain sufficient counts for adequate statistics ($10\sqrt{N}$). Again we are trying to detect a 0.01-percent leak from a single fuel pin. The results of such a calculation show that the counting time is increased by 50 percent. This does not affect the conclusions about counting continuously for both γ's.

Use of the lithium-drifted germanium detector would provide other advantages besides the ability to distinguish the I^{131}. It may be possible to distinguish other isotopes, the source of which may be corrosion of the piping or cladding material. The limits of detection of possible corrosion products have to be determined to see if this is feasible, but it may be possible to use a retention and decay period technique for this purpose only.

Finally, it appears that even though the primary coolant is highly radioactive, it may be possible to scan for and identify a relatively small fission gas leak (0.01 percent from one pin) by continuous scanning (~2-sec counting time) for the 0.364-MeV γ of I^{131}. More positive identification can be achieved by counting for 10-minute periods to confirm the presence of the 0.638-MeV γ of I^{131}. It is best to use the lithium-drifted germanium type detector because of its high resolution so that interfering radiations can be filtered out and perhaps identified as corrosion products.

It may also be wise to be looking for the γ rays from other volatile fission products that have a higher yield (higher activity) and escape more easily to the coolant. Recognition of γ peaks from two γ rays from the same isotope or from two different isotopes will provide verification if it is needed with the narrow-bandwidth lithium-drifted germanium detectors.

For a reactor design with more fuel elements or a greater primary coolant inventory, the time required for adequate statistics would be greater than that calculated for the specific reactor design herein considered.

CONCLUSIONS

An on-line fission-gas-leak detection system for the zirconium hydride reactor appears feasible in spite of the high background radioactivity in the coolant. The counting can be done on a continuous basis when looking for the 0.364-MeV γ of iodine-131 (I^{131}). A 2-second counting time will identify that γ ray. Verification can be obtained by counting for 10 minutes for the 0.638-MeV γ ray of I^{131}. Use of a lithium-drifted germanium detector appears to be the best choice. While counting time is increased by about 50 percent over a 7.6- by 7.6-centimeter (3- by 3-in.) sodium iodide (NaI) detector, the ability to distinguish between fission product activity and possible corrosion product activity makes it a necessary choice. The energy bandwidth of the scintillation-type device is so wide as to include radiations from other isotopes that could accumulate in the sodium potassium, such as iron-53, nickel-57, and chromium-51 from corrosion of the cladding and/or the stainless-steel piping. However, the bandwidth of the lithium-drifted germanium detector can be of the order of 0.006 MeV, compared to the 0.08 MeV of the NaI detector. This means that not only is it possible to easily distinguish the fission product activity, but it may also be possible to do some diagnostic corrosion study with the same equipment. The efficiency of the lithium-drifted germanium detectors is of the order of only 5 percent of that of the NaI type. This in combination with the narrower bandwidth results in a 50 percent increase in counting time. The improvement in resolution is well worth this increase in counting time. There were no isotopes that could be present in the NaK that would interfere with the counting of the two γ's from the I^{131}.

A further improvement would be to scan for fission products other than I^{131}. The isotope could have a higher yield and could provide indication of a smaller leak than the I^{131}. For instance, I^{134} has a fission yield of 6.7 percent and might provide information on a leak of 0.0042 percent from a single fuel element.

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Cleveland, Ohio, June 15, 1973,
503-25.

APPENDIX - SYMBOLS

A	fission product activity, dis/sec
C_1	activity of I^{131} measured by a detector
C_2	activity of background measured by same detector as in C_1 above
c	speed of light
$E_{max\ \beta}$	maximum energy of dislodged beta particle
E_0	energy of incident gamma
M_0	rest mass of electron - when combined with c^2 gives the energy associated with that mass
N	total number of background counts recorded by detector
P	reactor power in watts
t_c	time required for counting
y	fission product yield

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TABLE I. - ACTIVITY OF SODIUM POTASSIUM FOR VARIOUS DECAY PERIODS

Active specie	Half-life, hr	Decay constant, λ, per day	Decay period, days	Activity of NaK in a 100-kW reactor, dis/sec
Na^{24}	15.0	1.11	0	2.70×10^{10}
			3	9.67×10^{8}
			5	1.05×10^{8}
			6	3.46×10^{7}
			8	3.76×10^{6}
K^{42}	12.4	1.34	0	1.09×10^{10}
			3	1.95×10^{8}
			5	1.34×10^{7}
			6	3.51×10^{6}
			8	2.40×10^{5}
Total sum of Na^{24} and K^{42}			0	3.79×10^{10}
			3	1.16×10^{9}
			5	1.18×10^{8}
			6	3.81×10^{7}
			8	4.00×10^{6}

TABLE II. - ACTIVITY OF IODINE-131 AND SODIUM POTASSIUM FOR VARIOUS DECAY PERIODS

Decay time, days	Activity per kilogram of NaK, dis/sec	
	I^{131}	K
0	1.76×10^{6}	3.79×10^{10}
3	1.36×10^{6}	1.16×10^{9}
5	1.14×10^{6}	1.18×10^{8}
6	1.05×10^{6}	3.81×10^{7}
8	8.84×10^{5}	4.00×10^{6}

TABLE III. - MAXIMUM BETA ENERGIES AND BACKGROUND COUNTS

FOR SODIUM-24 AND POTASSIUM-42 GAMMAS

Isotope[a]	Gamma-ray energy, MeV	Maximum beta energy	Compton fraction	Total equilibrium activity per kilogram of NaK, γ/sec	Counts per second per MeV[b]
Na^{24}	1.37	1.155	0.65	2.70×10^{10}	1.52×10^{10}
Na^{24}	2.75	2.516	.80	2.70×10^{10}	8.59×10^{9}
K^{42}	1.52	1.30	.68	1.96×10^{9}	1.03×10^{9}
			Total	5.6×10^{10}	2.5×10^{10}

[a]Each disintegration of Na^{24} is accompanied by the emission of both a 1.37-MeV γ and a 2.75-MeV γ, while only 18 percent of the K^{42} disintegrations result in a 1.52-MeV γ, 82 percent yielding pure β decay.

[b]Assumes 100-percent counting efficiency for the 7.6- by 7.6-cm (3- by 3-in.) NaI detector.

TABLE IV. - SUMMARY OF DATA FOR PRIMARY

GAMMA RAYS EMITTED BY IODINE-131

	Gamma-ray energy, MeV	
	0.363	0.638
Fraction of disintegrations yielding gamma ray	0.849	0.069
Photofraction	.75	.55
Equilibrium activity per kilogram of NaK for 100-kilowatt reactor, counts/sec	1.12×10^{6}	6.7×10^{4}

TABLE V. - COMPARISON OF SODIUM POTASSIUM BACKGROUND ACTIVITY WITH IODINE-131 PHOTOFRACTION PEAK ACTIVITIES FOR VARIOUS DECAY PERIODS

Decay time, days	Source					
	Na^{24}		K^{42}	Total NaK	I^{131}	
	Gamma energy, MeV					
	1.37	2.75	1.52	---	0.364	0.638
	Half-life					
	15 hr		12.4 hr	---	8.05 days	
	Gamma rays within I^{131} photofraction peak, counts/sec/kg of NaK					
0	1.52×10^{10}	8.6×10^{9}	1.03×10^{9}	2.48×10^{10}	1.12×10^{6}	6.7×10^{4}
3	5.44×10^{8}	3.1×10^{8}	1.85×10^{7}	8.70×10^{8}	8.6×10^{5}	5.2×10^{4}
5	5.91×10^{7}	3.3×10^{7}	1.27×10^{6}	9.38×10^{7}	7.3×10^{5}	4.4×10^{4}
6	1.95×10^{7}	1.10×10^{7}	3.32×10^{5}	3.08×10^{7}	6.7×10^{5}	4.0×10^{4}
8	2.11×10^{6}	1.20×10^{6}	2.28×10^{4}	3.33×10^{6}	5.6×10^{5}	3.4×10^{4}
10	2.30×10^{5}	1.30×10^{5}	1.56×10^{3}	3.61×10^{5}	4.7×10^{5}	2.8×10^{4}

TABLE VI. - COUNTING TIME FOR $10\sqrt{N}$ COUNTS FOR VARIOUS DECAY PERIODS

Decay time, days	Gamma-ray energy, MeV	
	0.364	0.638
	Counting time, sec	
0	2.0	552
3	.12	32
5	.018	4.8
6	.007	1.9
8	.001	.29
10	.0002	.05

TABLE VII. - SOME ISOTOPES WITH GAMMA ENERGIES IN THE RANGE OF THE 0.364-MEV GAMMA OF IODINE-131 PEAK

Isotope	Gamma-ray energy, MeV	Source
Fe^{53}	0.370	Fe in NaK, piping, and cladding
Ni^{57}	.40	Ni in piping and cladding
Ni^{65}	.37	Ni, Zn, and Cu in NaK, piping, and cladding
Mo^{99}	.372	Mo in piping and cladding
Na^{25}	.40	Na in NaK

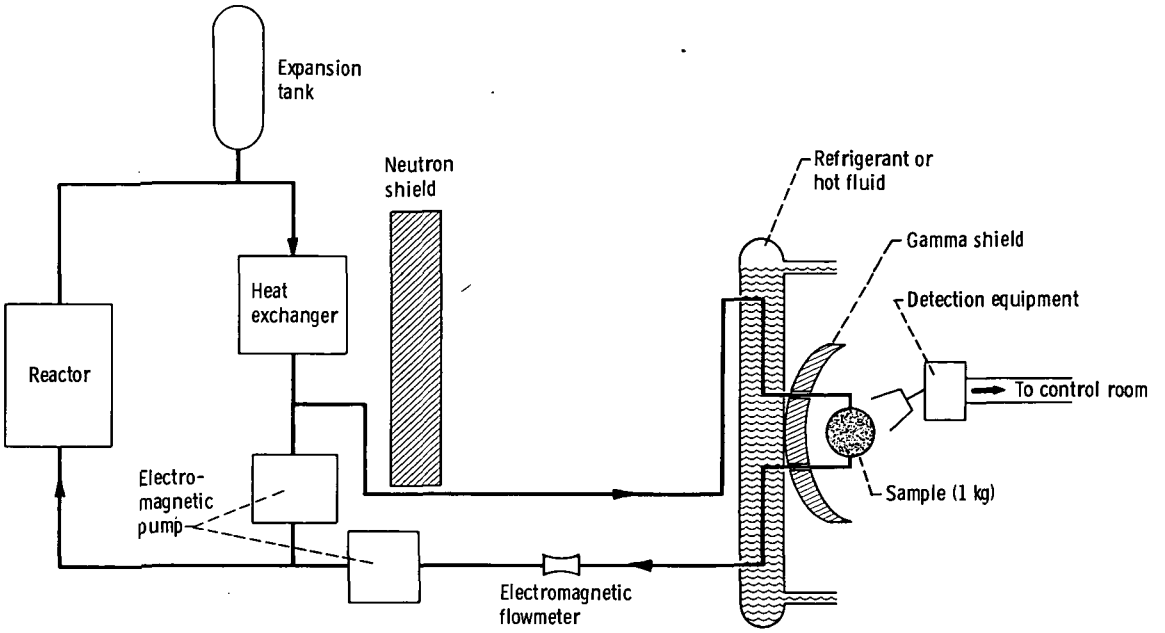

Figure 1. - Schematic of system with cladding-failure diagnostics in line.

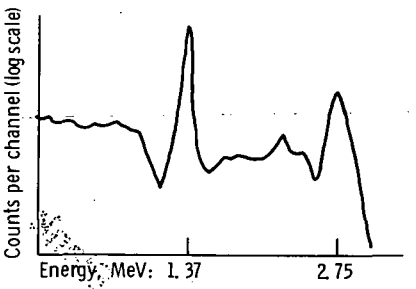

Figure 2. - Typical spectrum (Na^{24}) from multichannel scintillation counting.

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