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Design Study of a Megacurie Source

B. Manowitz, D. J. Metz, R. H. Bretton

Now that power reactors are in the design and construction stage, it is interesting to note that many of these reactors can economically produce megacurie amounts of cobalt-60. To get a feeling for the economic feasibility of such a scheme, consider the case of a reactor generating 500 megawatts of heat power. Each watt corresponds roughly to 3×10^{10} fissions per second, and each fission will release about 2.5 neutrons, one of which must be spent in continuing the chain reaction while the others are absorbed in the system. Allowing one of these latter neutrons to be captured in cobalt-59 will produce 3×10^{10} atoms of cobalt-60 per second, per watt, or, utilizing only 2 percent of the power of the reactor to be used in producing cobalt-60, there will have been produced

$$(10\times10^{6}\ \mathrm{w})\left(3\times10^{10}\ \frac{\text{atoms Co}^{60}}{\text{sec}}\right)\cdot\left(\frac{0.693}{5.2\ \mathrm{yr}\times3.17\times10^{7}\ \frac{\text{sec}}{\text{yr}}\times3.7\times10^{10}\ \frac{d}{\text{sec c}}}\right)\times3.17\times10^{7}\ \frac{\text{sec}}{\text{yr}}=$$

$$1\times10^{6}\ \text{curie of cobalt 60/yr}$$

The cobalt can so be placed in the reactor that it will actually improve upon, rather than hinder, the efficiency of heat removal. For instance, cobalt can be used for the control rods of the reactor; it can also be used in flattening positions in the reactor; that is, it can be placed in such positions that the neutron flux distribution will be flattened, thus making the temperature distribution more uniform throughout the system and improving on the efficiency of heat removal; finally, cobalt can be put into peripheral positions in the reactor where it will have little effect on the flux distribution but will catch neutrons that ordinarily would have been lost to the thermal shield—thus the duty for the secondary cooling system on the thermal shield could be reduced and more heat could be directed to the power cycle.

At any rate, it is feasible in many power reactor designs to incorporate space for cobalt in such positions that the neutrons absorbed are essentially free, and the true costs involved are the cost of fabricating the cobalt pieces and the infrequent operational cost of removing

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the cobalt from the reactor and transferring it into shipping casks. Calculations have been made of the specific activity of cobalt-60 to be expected by irradiating cobalt-59 at various flux levels, and they are presented in Table 1.

Assume that there is available a 500-megawatt reactor where one can make use of 10 megawatts of the power generated, and that the 10 megawatts is available at an average depressed flux of 2×10^{13} neutrons per square centimeter, per second. In order to produce a megacurie of cobalt-60 in 1 year, having a specific activity of approximately 22 curies per gram, one will have to insert in the reactor $10^6/22 = 4.55 \times 10^4$ grams of cobalt-59. Although the particular geometry of the individual pieces of cobalt may depend on the ultimate use of the radiation sources, for the purposes of this paper assume that the cobalt is fabricated into rectangular slabs 1 inch wide by 0.160 inch thick by 10 inches long, these dimensions including 0.030 inch of stainless steel cladding. Each element will contain 136 grams of cobalt and will have a total weight of 221 grams. Thus, a total of 334 of these elements will be required, each of which will contain approximately 3000 curies.

Table 1. Specific activity of cobalt-60 obtained by irradiating cobalt-59.

Neutron flux* (n/cm², sec)	Atom % of Co^{60} after 1 yr	Curies of Co^{60} per gram after 1 yr
10^{12}	0.100	1.17
10^{13}	0.990	11.6
10^{14}	9.52	111

* The flux used here is not the undepressed flux but the flux that the cobalt actually sees.

Radiation Levels

In use as a radiation source, these elements can be assembled in various ways. Assuming that a flat-plate geometry is desired, the radiation level to be expected immediately in front of the array (1 centimeter away in air) can be calculated by assuming that at this distance the source is essentially an infinite slab source of finite thickness. The radiation intensity, I, in roentgens per hour, at such a point is given by the expression:

$$I = \frac{1.52 \times 10^8 S_v \mu}{\nu} [1 - F_1(\nu h)] \quad (1)$$

where S_v is the specific activity in curies per cubic inch, μ is the absorption coefficient of the gamma rays in air, ν is the absorption coefficient of the source material, h is the thickness of the source, and $F_1(\nu h)$ is defined as

$$F_1(\nu h) = \int_1^\infty x^2 e^{-\nu h x} dx \quad (2)$$

the so-called Gold integral. Taking the values $S_v = 3210$ curies per cubic inch (averaged over entire array), $\mu = 1.74 \times 10^{-4}$ per inch, and $\nu = 1.19$ per inch (an average for the relative amounts of stainless steel and cobalt), Eq. 1 reduces to

$$I = 7.18 \times 10^7 [1 - F_1(\nu h)] \quad (3)$$

The results of applying Eq. 3 to a range of thicknesses of the source are shown graphically in Fig. 1, where the radiation intensity at 1 centimeter in air from the center of a flat plate made by assembling the 334 elements into a roughly square sheet is plotted against the thickness. The radiation level near the surface of the most extended array ($h = 0.160$ inch) is 2.97×10^7 roentgens per hour and approaches an asymptotic value of 7.18×10^7 roentgens per hour as the array is condensed to a rough cube many elements thick.

Shipping-Container Problem

Plotted in the same figure are the tons of lead shield necessary to reduce the radiation level to 100 milliroentgens per hour (or lower at the ends) on the outer surface of the container. This value approaches an asymptotic value of 6.5 tons. Figure 2 is a plan view of the shielded array.

It would appear then that it might be feasible to design a shipping container to transport safely and store a megacurie of cobalt-60, if the only concern were safeguarding against the radiation emitted by the source. However, this quantity of cobalt-60 would generate 15 kilowatts of power, all of which would be dissipated as heat within the source itself and the shield material. Thus, serious thought must be given to the proper design of a container for a megacurie of activity that will properly shield against radiation and, at the same time, provide for the safe dissipation of the heat energy thus generated.

The first question to be resolved is whether or not multiple shipments of quantities of less than 1 million curies are to be considered. By reducing the curies per shipment sufficiently, one may effectively eliminate one of the main design problems—the removal of heat generated by the source. However, the weight of shielding required does not decrease in proportion. As a means of illustration, a 3000-curie source in the form of one of the afore-mentioned metal strips would probably require about 1.5 tons of shielding, but one could neglect the heat-removal problem.

It is shown in subsequent paragraphs that a suitable facility for transporting 1 million curies can be designed, which would weigh less than 15 tons, but the heat-removal problem must be given careful consideration. On the basis of

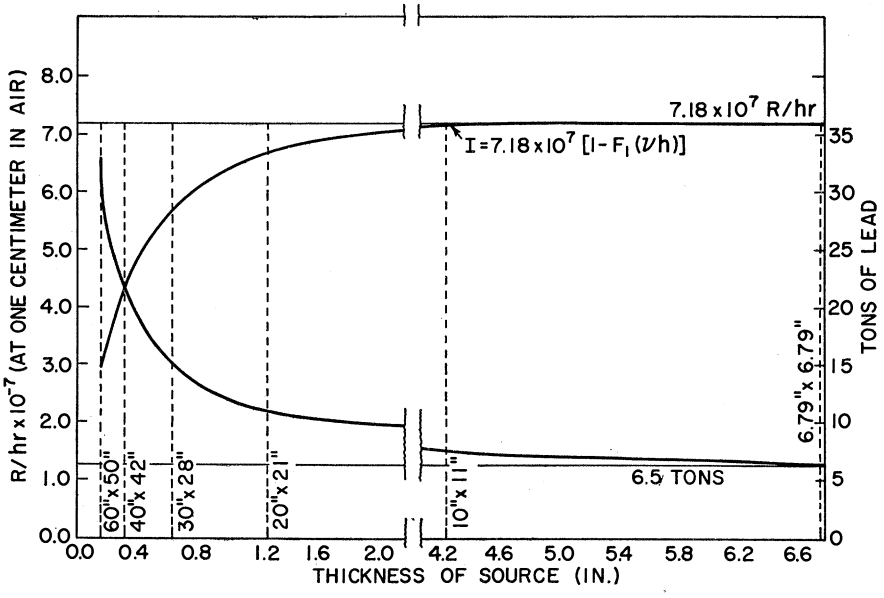

Fig. 1. Results of applying radiation intensity to a range of thicknesses of the source.

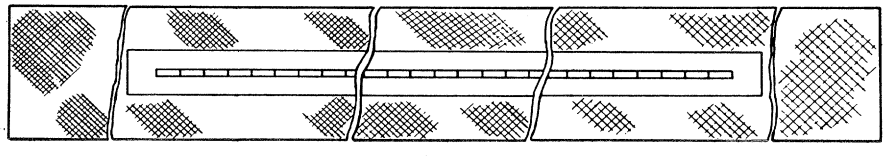

Fig. 2. Array for shielding and intensity calculations.

equal weight, 48 shipments each, consisting of seven of the 3000 curie sources, would be required for the transportation of 1 million curies as compared with one shipment with the single facility. Obviously, there are intermediate cases that compare much more favorably than the illustration given here, but this illustration does lend justification to considering the transportation in a single shipment, which is done in the discussion to follow. It might be added that a facility for transporting 0.5 million curies, rather than 1 million, would not differ significantly from the one to be described below.

Table 2. Temperature values for a megacurie source.

Air circulation rate (lb/hr)	Assumed emissivity of stainless steel surface	t_1* (°F)	t_2* (°F)	t_3* (°F)	t_4* (°F)	Remarks
0	1	340	444	510		No air circulation
0	0.5	410	516	590		No air circulation
162	0.5	317	350	440	353	Natural circulation; no stack
400	0.5	273	300	350	308	Natural circulation; 6.4 ft. stack
1000	0.5	185	200	245	210	Forced convection

* It will be noted that in most cases these are maximum temperatures for the general location.

Before proceeding any further, it might be well to state qualitatively some of the requirements that should be met by a properly designed facility. (i) The facility must be properly shielded. (ii) The temperature in the lead shield must always be below the melting point of lead, since any small crack developing in the container during shipment might result in complete loss of shield if the lead were in a molten state. (iii) The use of power-driven auxiliary equipment should be avoided, if possible, since loss of power might lead to intolerable conditions. (iv) It should be borne in mind that the facility must be loaded and unloaded and, hence, should be designed to permit such operation without leading to intolerable conditions. (v) In general, the temperatures throughout the facility should be as low as possible to reduce thermal stresses in the shield container and also in the cobalt strips themselves to prevent, in the latter case, rupture of the stainless steel sheath.

In all probability, the use of water as a heat-removal agent would result in the smallest size practical facility for transporting 1 million curies. However, there are potential hazards involved with the possible physical loss of coolant. Consequently, it was decided to attempt a design that would use air as a coolant and heat-transfer media.

All the heat generated in the cobalt must be transferred across an air gap which offers a large resistance to transfer and thereby results in a very large temperature difference. It is readily apparent that this could be avoided if the gamma radiation were absorbed in shield material rather than in the cobalt. This can be accomplished by dividing the entire cobalt mass into smaller masses, each surrounded by shield material. In order to determine the extent of subdivision necessary, one requires information on the fraction of gamma energy that is absorbed in various geometric shapes. Of particular interest in this design is the fraction absorbed in flat strips. For an infinite flat plate of thickness "b," the following equation may be derived:

$$f_a = 1 - \frac{1}{2\mu b}(1 - e^{-\mu b}) - \frac{1}{2}e^{-\mu b} + \frac{\mu b}{2}\int_{\mu b}^{\infty}\frac{e^{-x}}{x}\,dx \qquad (4)$$

where f_a is the fraction of gamma energy that is absorbed, μ is absorption coefficient, and b is plate thickness.

The integral expression in Eq. 4 can be evaluated from available tables. For an infinite plate of thickness corresponding to one of the afore-mentioned cobalt strips, the fraction of gamma energy absorbed would be 0.30. For an actual finite strip of the dimensions given here, the value would be less than this. It has been estimated that in such a strip the fraction of the total energy absorbed (both β and γ) would be about 0.33, assuming that the beta energy (amounting to 11.5 percent) is totally absorbed by the cobalt.

It is obvious from this calculation that, if most of the energy is to be absorbed in the shield material, then individual strips must be used, each surrounded by shield material. Thus, a practical facility would consist of a shield block containing a central core consisting of a large number of slots, each containing one or more cobalt strips. This is surrounded by further shielding to reduce the intensity of radiation to a tolerable value at the surface. One proposed design is shown in Fig. 3.

The spacing between slots must be given careful consideration. If the slots are too close, then the contribution of nearby strips to the absorption in any one particular strip will be excessive, and the figure of 33 percent given in a foregoing paragraph would be raised appreciably. On the other hand, too great a spacing would add unnecessarily to the size and weight of the facility. An arrangement allowing 0.5 inch of shielding material between strips was selected after consideration had been given to the afore-mentioned factors. Another result of subdividing the total mass of cobalt is the increase in area available for heat transfer. Rectangular slots were selected in preference to circular ones, mainly because this particular geometry allows more shield material in the central core.

To increase the efficiency of the facility with regard to the removal of heat, the facility has been designed to permit natural circulation of air through the slots. This has been done by means of a large number of connecting tubes, as is shown in Fig. 3. The number and size of tubes is governed by two factors: (i) the pressure drop through the facility and (ii) the level of radiation scattered through the tubes. It will be observed that none of the cobalt strips actually sees out the

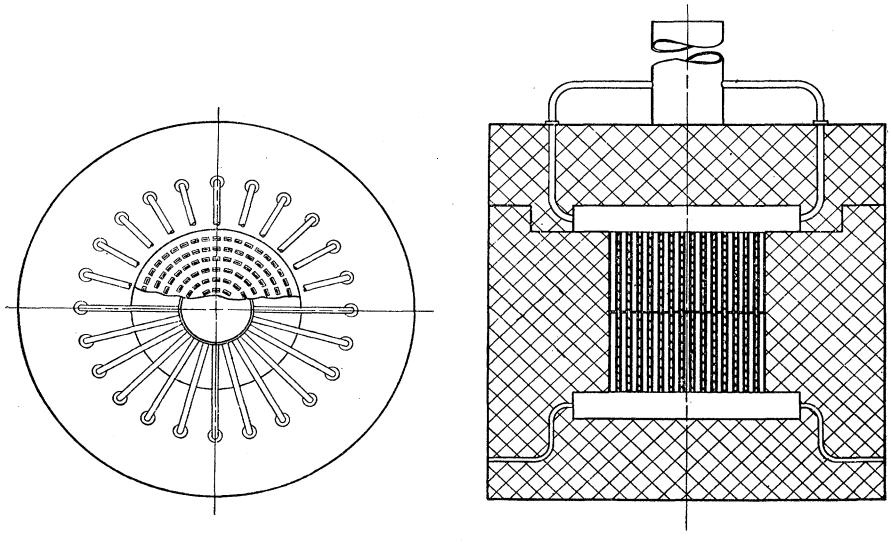

Fig. 3. Shielded container for megacurie source.

tubes, and hence radiation reaching the outside must arise from multiple scattering processes. This consideration requires that the tubes be small.

The fluid-flow relationships involved either require relatively few large tubes or a large number of small tubes. With respect to the fluid-flow relationship, the criterion used was to make the largest individual pressure drop be that associated with the slots, since their size, as described here, is governed by other factors and not easily subject to change. As a result, many small tubes are used. The natural circulation can be improved by adding a stack to the facility, as is shown.

The over-all dimensions of such a proposed facility would be about 4 feet in diameter by 4 feet in height, with a 6-foot stack having an internal diameter of about 10 inches. The weight of such a unit would be about 13.5 tons. The inner cylindrical core (containing the rectangular slots) would be about 2 feet in diameter by 2 feet in height. Each slot would contain two cobalt strips arranged vertically, one above the other. Since 334 strips are required to constitute a megacurie, 167 slots would be required, and these would be arranged on concentric circles spaced 1½ inches apart. Each rod in a given circle would also be about 1.5 inches apart, from center to center. Since each slot is 1 inch by 0.5 inch, the thickness of lead between slots (and hence between cobalt strips) would be 1 inch in a radial direction and 0.5 inch along the circumference of the circle. The air chambers above and below the central core would be 4 inches in height, and there would be 100 1-inch tubes in the top and bottom sections to permit circulation of air.

The temperatures of interest in such a facility are those at the outer surface, in the central core, and in the individual cobalt strips. Since these temperatures are dependent on position, the values given in Table 2 refer to specific locations as follows: t_1 is the temperature of the outer surface at a point midway between top and bottom; t_2 is the temperature at the center of the core; t_3 is the temperature at the center of a cobalt strip; and t_4 is the temperature of the air in the tubes leaving the facility. The calculations that led to the results given here involved many assumptions and approximations, which are too numerous and too involved to discuss in this paper.

Bendix Time-of-Flight Mass Spectrometer

W. C. Wiley

The combination of high resolution with the speed of response and geometric simplicity of time-of-flight mass spectrometers makes possible the application of mass spectrometry to a number of analysis and research problems which heretofore have not been well suited to this technique. The development of the Bendix spectrometer began with the invention of a new ion gun (*1*) which was capable of providing very high resolving power when used in a time-of-flight mass spectrometer. Further development work was encouraged by the inherent versatility of the instrument both in its operation and in its design. Several models have now been designed and built on special order to satisfy a number of different applications. Following a description of the spectrometer's operation and a summary of its characteristics, some of these applications are discussed.

Operation

Several classes of mass spectrometers are commonly referred to as time-of-flight instruments. The Bendix spectrometer belongs to the class which probably represents the most straightforward application of time of flight to mass spectrometry and, in its simplest form, consists merely of an ion source and an ion collector situated at opposite ends of an evacuated tube, as is shown in Fig. 1.

Ions are first formed, usually by electron bombardment, between the two electrodes of the ion source. By applying a voltage pulse between these electrodes, the ion bunch can be ejected through an opening or grid in one of the electrodes. Because the ions, as a result of the accelerating field, reach a velocity that is a function of their mass to charge ratio, the original bunch of ions separates as it passes through the field-free region between the source and the detector into several bunches, each containing ions of a specific mass to charge ratio. Hence, the light ions will reach the ion detector first, followed in succession by the heavier ions.

One of the many methods in which the Bendix spectrometer can be operated is described in more detail with the aid of Fig. 2. The first event in the creation of a single mass spectrum, many thousands of which may be formed every second, is the establishment of the electron beam in the temporarily field-free ionizing region. This beam, which usually lasts a fraction of a microsecond, is produced when electrons are drawn off a hot filament by a voltage pulse applied to the adjacent electrode. After this beam is turned off, grid 1 is pulsed to eject the resulting ion bunch into the accelerating region. The direct-current source potentials are arranged so that the ions receive their major acceleration as they pass through this area on their way to the field-free separating region or drift space.

If the ions before pulsing were at rest and all in a plane parallel to the electrodes, almost any method of ejecting them from the source would provide infinite mass resolution, regardless of the total length of the flight path. The resolving power of the instrument is, therefore, a measure of the ability of the source to deliver the ions of one mass to charge ratio to the detector in a sharp pulse, even though the ions will inevitably vary in initial position and velocity. The effect of variations in the ions' initial position can be reduced by taking advantage of the fact that those ions farther away from grid 1 fall through a larger potential during the ion-ejection period than do those nearer this grid. The trailing ions will, therefore, acquire a greater velocity and will eventually overtake those in front. A proper adjustment of the fields in the ionizing and accelerating regions, usually made by varying the height of the ion-ejecting pulse applied to grid 1, causes the "crossover point" for all ion peaks to occur as they pass through grid 3 into the ion detector. The deleterious effect of initial ion velocities on the resolution of a time-of-flight spectrometer can be reduced in two ways: (i) the final velocity of the ions can be

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