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UNITED STATES ATOMIC ENERGY COMMISSION

EXPLORATORY STUDY: HOMOGENEOUS REACTORS AS GAMMA IRRADIATION SOURCES

By
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July 5, 1956

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Oak Ridge, Tennessee

Technical Information Service Extension, Oak Ridge, Tenn.

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I

Chemical Technology Division

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E. D. Arnold
A. T. Gresky

July 5, 1956

Work performed under Contract No. W-7405-Eng-26

Oak Ridge National Laboratory
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1.0 INTRODUCTION

In a March 27 letter from S. R. Sapirie to C. E. Center, it was requested that a brief feasibility study be made of homogeneous reactors for use as gamma irradiation sources. The need for such a study was to supplant an investigation by the APB and the Army Quartermaster Corps. in a broader survey of various reactor types which may be employed in conjunction with food irradiation facilities. The scope of the study was to define problem areas which would form bases for possible future, more detailed studies, e.g., by an ORSORT, or other, study group.

A preliminary survey of literature on the subject revealed that considerable thought has already been given to the estimations of design and costs^{1,2} in such a reactor scheme. Therefore, this memo serves mainly to summarize the thinking in those previous studies, and to supplement the information concerning the specific case for homogeneous reactors. An appendix is included to provide essential background information concerning the broader subject problems of food irradiation and requirements of proposed facilities.

Radiation requirements, which set the bases for the sizing of reactors and irradiation facilities, were provided as follows:

1. It is assumed that items to be exposed in the irradiation facility will require doses from 10,000 rep to 10^7 rep. Doses required for foods will be under 6×10^6 rep, with most items being given 2×10^6 rep or less.
2. Maximum dose rate is to exceed 1×10^6 rep/hr in order to minimize the size of the irradiation volume and the time of exposure.
3. The source should be capable of delivering a dose of two mega-rep to 1,000 tons of food or other substances of unit density per month, assuming operation on a continual basis. However, it is assumed that there will be frequent shutdowns to permit modifications in food processing lines, thus reducing the actual output of the radiation source.

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4. The radiation volume should be capable of handling continuously:

- (a) Items of unit density of sizes from No. 2 cans (3-7/16" D x 4-9/16" H) up to V3 boxes (6" x 16" x 20").
- (b) Sacks of flour, potatoes, etc.
- (c) An overhead trolley to permit treatment of carcasses, military equipment, etc.

5. Temperature of radiation volume should be capable of being controlled within 5 degrees over a range of minus 20° to plus 75°C.

6. Dosage delivered is to be within 15% of the required amount. This is an outside figure, with a maximum variation in dose being within 10% if this can be obtained.

7. Investigations at the MTR have shown that foods irradiated in the canal have been exposed to neutron fluxes of about 10^4 neutrons/cm²/sec for periods of as long as a half hour with the production of no detectable radioactivity in either food or container. (Since each fuel element in the irradiation facility was placed in a cadmium-lined slot, it can be assumed that most of this flux was due to the (gamma,n) reaction of the deuterium in the canal water with gamma photons of over 2.23 Mev energy.) Based on these observations, it would appear that a total maximum dose of 1.8×10^7 neutrons/cm² is acceptable. This figure corresponds closely with the maximum allowable personnel dose of neutrons as determined from data listed in NBS Handbook 52.

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2.0 CONCLUSIONS

For single purpose reactors, i.e. those designed exclusively as irradiation sources for food sterilization, homogeneous reactors can offer no significant advantages over other types of reactors with respect to either economic or operational feasibility. Unit costs of 4.5 to 6.0 cents per pound of irradiated meat compare closely with that found for heterogeneous types.

However, very significant economic advantages exist for double-purpose reactors, i.e. those which can produce useful electrical power and also serve as food irradiation sources. Such reactors, at heat power levels of about 300 MW and with by-product utilization of off-gas, hydroclone underflow, and/or core solutions, can conceivably irradiate meat at a remarkably low cost of 0.3 cents per pound, a factor of about 20 less than for single-purpose types. Such reactors also offer a wide range of flexibility in the irradiation levels which may be required of a facility. It may be pointed out that heterogeneous types cannot compete in this way, since no feasible engineering method is evident for such by-product utilization of gamma radiations.

Hypothetically, the above would indicate that in a combination power-irradiation unit, homogeneous reactors could totally write-off their electrical power costs if a price of 1.8 cents per pound of irradiated meat was charged to the associated irradiation facility.

Although those interested in the business of food irradiation would basically prefer isolation from the power industry per se, it would seem that the large economic advantages offered by the homogeneous power reactors should not be overlooked, especially in the future large-scale potentials of radiation utilization.

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3.0 DISCUSSION

The various types of homogeneous reactor concepts which may be considered as feasible food irradiation sources may be placed in categories as follows:

- I Activation of Circulating Solution
 - (a) D_2O moderated - no power
 - (b) H_2O moderated - no power
- II Utilization of Rare Gas Fission Products
 - (a) D_2O moderated - no power
 - (b) D_2O moderated - power
- III Utilization of Clone Underflow
 - (a) D_2O moderated - power
- IV Utilization of Core Solution
 - (a) D_2O moderated - power
- V Combination of II-IV - Power

If economic considerations are emphasized, the by-product utilization of rare gas, clone underflow, and/or core solution from a large-scale electrical power producer, i.e., 3-400 Mw class, would certainly provide a minimum cost per pound of irradiated meat. This cost would be about 0.28 to 1.45 cents per pound based on 40 tons per day processing, and would compare very favorably with the lowest costs so far reported, e.g., the linear accelerators at 2.4 cents per pound. However, it is generally stated that food processors prefer independence from power stations, so the above cases reflecting power production are treated as economic limits and are not compared directly with the single-purpose, no-power cases proposed for heterogeneous reactors.

The cases for independent facilities and (1) activation of a clean-core circulating solution or (2) the utilization of rare gases afford the most legitimate comparisons with other proposals. These cases would be characterized by costs in the order of 5 to 6 cents per pound of meat. Reactor data and preliminary cost estimates for the three most pertinent cases are compared with two similar heterogeneous cases previously reported by an ORSORT study group. See Tables 3.1 and 3.2.

Table 3.1

Comparison of Reactor Data

	Heterogeneous Types (Clean Core)		Homogeneous Types		
	Power	No Power	1	2	Rare Gas
Power Producer	Yes	No	No	No	No
Metal to Total Ratio	0.2	0.2	--	--	--
Moderator	H ₂ O	H ₂ O	D ₂ O	H ₂ O	D ₂ O
Blanket Poison, Σ , cm ⁻¹	0.2	0.2	0.2	0.2	--
Reactor Radius, cm	40	40	80	40	80
Blanket Thickness, cm	16	16	16	16	--
Reactor Power, Mw					
100 min Processing Time	31	17	16.5	34	43
10 min Processing Time	--	--	30	62	--
Avg. Core Flux n/cm ² /sec					
100 min Processing Time	5.6x10 ¹³	6.2x10 ¹³	6.3x10 ¹³	6.0x10 ¹³	1.6x10 ¹⁴
Power Density					
100 min Processing, Kw/l	230(Max)	207(Max)	24(Avg.)	127(Avg)	63(Avg.)
Fuel Loading, Kg(Total)	11.80	6.88	26.5	120	46.5
Fuel Loading, Kg (Core)	11.80	6.88	6.4	13.7	6.4

Table 3.2 Cost Estimates for Several Food Irradiation Reactors

	1	2	3	4	5
	Heterogeneous (Clean Core-Power)	Heterogeneous (Clean Core-No Power)	Homogeneous (D ₂ O Mod.-No Power)	Homogeneous (H ₂ O Mod.-No Power)	Homogeneous (D ₂ O Mod.-Rare Gas)
<u>REACTOR</u>					
Pressure Vessel	100,300	26,000	25,000	18,000	25,000
Thermal Shield	4,360	4,360	15,000	10,000	15,000
Fuel Assembly or Core Vessel	63,000	22,000	70,000	20,000	70,000
Biological Shield	41,200	41,200	100,000	100,000	100,000
Control System	100,000	50,000	100,000	100,000	100,000
Fuel Cost					
<u>PRIMARY COOLANT LOOP</u>					
Pressurizer System	30,000		20,000	20,000	35,000
Ht. Exch./Steam Drum	155,000	149,000	179,000	390,000	313,000
Dump Tank	8,000	5,000	6,000	7,000	10,000
Pipe and Valves	58,000	20,000	24,000	58,000	42,000
Pumps and Motors	140,000	106,000	127,000	185,000	222,000
<u>STEAM POWER PLANT</u>	854,000				
<u>BLANKET LOOP</u>					
Pipe and Valves	3,600	4,000	4,000	4,000	
Pumps and Motors	25,000	25,000	25,000	25,000	25,000 (Gas Loop)
Flash Cooler	2,000	2,000	2,000	2,000	
Surface Cond. or Heat Exchanger	15,000	15,000	15,000	15,000	
Solution Make-up Equipment	5,000	5,000	5,000	5,000	
Dump Tank	7,200	7,200	7,200	7,200	
<u>PROCESS INSTRUMENTATION</u>	100,000	100,000	100,000	100,000	100,000
<u>SHIELD COOLING SYSTEM</u>	25,000	25,000	25,000	25,000	25,000
<u>EMERGENCY COOLING TANK</u>	20,000	20,000	20,000	20,000	20,000
<u>ACTIVATED SOLUTION CHEMICALS</u>	10,000	10,000	10,000	10,000	
<u>H₂O PURIFICATION</u>		50,000			
<u>STACK</u>	10,000	10,000	10,000	10,000	10,000
<u>HOT CELLS</u>	450,000	350,000	350,000	350,000	350,000
<u>CORE HANDLING EQUIPMENT</u>	20,000	20,000			
<u>CRAINE</u>	100,000	100,000	100,000	100,000	100,000
<u>IRRADIATION FACILITY</u>	163,000	163,000	163,000	163,000	163,000
<u>BUILDING AND SITE DEVELOPMENT (Erected Cost)</u>	655,000	585,000	585,000	585,000	585,000
<u>TOTAL MATERIALS AND LABOR</u>	3,164,660	1,768,160	2,087,200	2,329,200	2,320,500
<u>30% CONTINGENCIES</u>	949,400	535,000	626,200	698,800	696,200
<u>SUB-TOTAL</u>	4,114,060	2,303,160	2,713,400	3,028,000	3,016,700
<u>10% ENGINEERING</u>	411,400	230,000	271,300	302,800	301,700
<u>45% CONTRACTOR</u>	1,851,300	1,036,400	1,221,000	1,362,600	1,357,500
<u>TOTAL COST</u>	6,376,760	3,569,560	4,205,700	4,693,400	4,675,900
<u>LAND ONLY</u>	- 250,000	- 250,000	- 250,000	- 250,000	- 250,000
<u>NET COST</u>	6,126,760	3,319,560	3,955,700	4,443,400	4,425,900
<u>CRITICAL MASS (Kg)</u>	9.40	5.50	6.4(core)	13.7(core)	6.4(core)
<u>EXCESS MASS (B.U. Xe) (Kg)</u>	2.40	1.38			
<u>TOTAL LOADING (Kg)</u>	11.80	6.88	26.5(system)	120(system)	46.5

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	1	2	3	4	5
<u>FUEL COST (\$20 per gram)</u>	236,500	133,500	530,000	2,400,000	930,000
<u>ANNUAL FUEL INVENTORY CHARGE</u>	9,440	5,300	21,200	96,000	37,200
<u>D₂O INVENTORY AND LOSS</u>			23,000		40,400
<u>ANNUAL BURNUP (Kg)</u>	13.35	7.04	8.0	16.2	20.5
<u>ANNUAL BURNUP CHARGE (\$20 per gram)</u>	267,000	140,700	160,000	324,000	410,000
<u>ANNUAL REPROCESSING CHARGE</u>	133,000	73,500	75,000	75,000	75,000
<u>ANNUAL REFABRICATION CHARGE</u>	295,000	5,600	0.0	0.0	0.0
<u>TOTAL ANNUAL FUEL CHARGE</u>	704,000	325,000	279,200	505,000	562,600
<u>TOTAL ADJUSTED FUEL CHARGES*</u>	459,000	212,000	181,200	328,000	365,000
<hr/>					
<u>REACTOR HEAT POWER, Mw</u>	31	17	16.5	34	43
<u>GROSS THERMAL EFFICIENCY</u>	0.25	0.25	0.25	0.25	0.25
<u>POWER PLANT GROSS CAPACITY, Kw</u>	7,750	4,260	4,125	8,500	10,700
<u>OPERATING TIME: Hrs/Week</u>					
Manufacturing	50	50	50	50	50
Generating	59	59	59	59	59
<hr/>					
<u>POWER CREDITS AND/OR DEBITS**</u>					
Manufacturing 10% of General	16	- 16	- 16	- 16	- 16
Manufacturing 90% of General	6				
Generating only 90% of General	2				
<u>ANNUAL CREDITS ALLOTTED TO PLANT AUXILIARY</u>	32,200				
<u>ANNUAL CREDITS ALLOTTED TO MFG. PERIOD SALES</u>	109,000				
<u>ANNUAL CREDITS ALLOTTED TO OFF TIME</u>	45,100				
<u>TOTAL ANNUAL POWER CREDITS OR DEBITS</u>	186,300	- 19,300	- 18,700	- 38,700	- 48,700
<hr/>					
<u>TOTAL CAPITAL COST, \$(Depr. Items)</u>	6,126,760	3,319,560	3,955,700	4,443,400	4,415,900
<u>TOTAL CAPITAL COST LAND</u>	250,000	250,000	250,000	250,000	250,000
<u>ANNUAL CHARGES:</u>					
Fixed Charges, Land (12%)	30,000	30,000	30,000	30,000	30,000
Fixed Charges (15% Depr. Items)	919,000	497,900	593,300	666,500	663,900
Fuel Charges	459,000	212,300	181,200	328,000	365,000
Operation and Maintenance (25% F.C.)	237,000	132,000	156,000	174,000	173,000
<u>TOTAL ANNUAL COSTS</u>	1,545,000	872,200	960,500	1,198,500	1,231,900
<u>ANNUAL DEBITS</u>		19,300	18,700	38,700	48,700
<u>ANNUAL POWER CREDITS, \$</u>	186,300				
<u>NET ANNUAL COST OF OPERATION, \$</u>	1,358,700	891,500	979,200	1,237,200	1,280,600
<u>NET COST PER POUND OF MEAT, Cents</u>	6.5	4.3	4.7	5.9	6.1

*Adjusted fuel charges for intermittent cases obtained by multiplying total annual fuel charges by ratio 109/168, i.e., by ratio of weekly operating hours to total weekly hours.

**Debits indicated by - sign.

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The costs listed in the above tables for the two heterogeneous cases designed by the ORSORT study group are not the same costs given by this group. The difference in the costs is due to a change in the contingency, engineering, and contractor factors. The ORSORT group used a factor of 10% for each while this report uses 30% for contingencies, 10% for engineering, and 45% for contractor. It is felt that these factors are more in line with present AEC construction practices.

The following general discussion of the individual reactor systems and variations in the design of irradiation facilities is presented to indicate the nature of problems which will be associated with more detailed analyses. Extracts from ORNL CF 55-8-190 are appended.

3.1 Use of a Two-Region Homogeneous Reactor

A two-region homogeneous reactor with a U^{235} sulfate solution (in either D_2O or H_2O) core and an indium sulfate blanket may be used as a food irradiation reactor. This type would thus be similar to the "clean core" heterogeneous reactor designed by the ORSORT group since neutrons produced in the core would be used to irradiate indium sulfate in the blanket. The indium sulfate solution in turn would be pumped to the irradiation facility.

The two reactors would be similar in power level and blanket volume. The irradiation facility for the homogeneous system would be an exact duplicate of the one described in Sec. 4.1. Cost-wise there would be no advantage in using a homogeneous reactor instead of a heterogeneous reactor, at least for the single-purpose scheme.

The homogeneous reactor would have an advantage in chemical processing and refabrication costs but would have a distinct disadvantage since a greater inventory of fissionable material would be necessary due to the holdup in the external loop.

3.2 Use of Off-Gas from Homogeneous Reactor

The radioactive off-gas from a homogeneous reactor could also be used as a source of gamma radiation. In this case, the radioactive gases, after leaving the recombiner, would be piped to the irradiation facility and then to the charcoal beds instead of going to the beds directly.

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For the irradiation of 40 tons beef/day to 2×10^6 rep, a total source activity, $S_0 V_0$, $\sim 7.5 \times 10^{17}$ d/s or 2.03×10^7 curies would be needed. From the data of Haubenreich,⁴ there would be 2.4×10^6 curies from the 5 Mw HRT assuming 3 min lag time between formation and utilization. Thus the power of the reactor may be scaled to be

$$\frac{2.03 \times 10^7}{2.4 \times 10^6} \times 5 = 43 \text{ Mw}$$

If the lag time is decreased to zero, then the reactor power may be reduced to 26 Mw, since the at-time-of-discharge activity of the gaseous fission products is $\sim 4 \times 10^6$ curies for a 5 Mw reactor.

Control of the gaseous fission product source will be accomplished by gas dilution. With a total source activity of 7.5×10^{17} d/s and an average half-life of one hour for the gaseous fission products the fission product gas pressure only need be ~ 8 mm Hg in the 5' x 6' x 1' source container.

Since this reactor will require a higher power than the indium sulfate reactor to accomplish the same irradiation there is apparently no advantage to such a system for a single purpose reactor. The unit cost for this system is greater than the other four cases listed. This unit cost is 6.1 ¢/lb beef as compared to 4.3 ¢/lb for the optimum reactor using a heterogeneous core and an indium sulfate blanket. The advantage of utilization of the gaseous fission products would come from a dual purpose reactor which operates at a much higher power for the sale of electricity.

The reactor data pertaining to this scheme appears in Table 3.1 and the cost estimate is shown in Table 3.3. Further information about the use of gaseous fission products may be found in the appendix. (See Section 4.1.5)

3.3 Use of Hydroclone Underflow from Homogeneous Power Reactor

Another possible application for a homogeneous reactor for food irradiation would be the use of the hydroclone underflow as the source of gamma radiation. The use of hydroclone underflow would definitely tie the radiation facility to a power reactor. Assuming a two-day decay of

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Table 3.3

Rare Gas Utilization in Conjunction with A Large-Scale Power Station*

(Estimated costs associated with gas loop and irradiation facilities)

Gas Loop	\$ 25,000
Hot Cells	350,000
Irradiation Facility	163,000
Building and Site	<u>100,000</u>
Total Materials and Labor	\$ 638,000
30% Contingency	<u>191,400</u>
Subtotal	\$ 829,400
10% Engineering	83,000
45% Contractor	<u>373,200</u>
Total Cost	\$1,285,600
Fixed Charge, 15%	192,500
Operation and Maintenance (10 people)	100,000
Water, Power, etc.	<u>10,000</u>
Net Annual Operating Cost	\$ 302,000
Net cost per pound of meat, cents	1.45

* 43 Mw heat necessary at 2×10^6 rep.

(Approximate net cost would be 0.5 cents for irradiation of 200 tons per day at 2×10^6 rep, or 2.5 cents for 40 tons per day at 10^7 rep. The power of the reactor core would be 215 Mw.)

fission products in the underflow before use in the irradiation facility, a minimum core power of 231 Mw would be necessary in order to contribute 17 Kw irradiation level assuming 17% utilization efficiency and 100% volume efficiency based on underflow volume. This power level can be obtained from the following assumptions:

(a) The fission product power due to fission products having a half-life ≥ 2 days would be 30 γ -watts/day-Mw reactor power.

(b) The average half-life over the first few days' decay would be 10 days.

(c) The above are based on a reactor processing cycle of 190 days through solvent extraction, one day through hydroclones, and with complete removal of rare earths and alkaline earths in the hydroclone underflow. Therefore, the minimum power level of the reactor core may be calculated from the following relationship:

$$\frac{dA}{dt} = 30 P - \frac{17000\lambda}{E} - \frac{17000C}{E} = 0$$

where 17000 = theoretical power for irradiation

E = efficiency = 17%

$\lambda = 0.693/t_{1/2} = 0.693/10 = 6.93 \times 10^{-2} \text{ days}^{-1}$

C = chemical removal rate from facility = $1/T_p$, days^{-1}

T_p = chemical removal per vol, days

$$30 P - 100,000 \times 6.93 \times 10^{-2} - 100,000 C$$

For minimum power, assume C = 0

$$\text{Then } P = \frac{6.93 \times 10^3}{30} = 231 \text{ Mw}$$

Since C cannot be zero, the actual core power must be greater than 231 Mw. For economic and solvent extraction considerations, T_p should be in the order of 30 days since this would be the most probable decay time prior to solvent extraction. Then the actual core power may be estimated to be:

$$P = \frac{6.93 \times 10^3 + 1 \times 10^5/30}{30}$$

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$$P = \frac{6.93 \times 10^3 + 3.33 \times 10^3}{30} = 342 \text{ Mw}$$

The irradiation source is thus used as the decay tank for the hydroclone underflow solution. However, the source must be designed to be critically safe.

3.4 Use of Core Solution from Homogeneous Power Reactor

The best source of gamma radiation in homogeneous reactors would be the core solution itself. However this gamma radiation cannot be used directly since there will be a high neutron flux due to the delayed neutron fraction existing in the irradiator itself. The average energy of these delayed neutrons is approximately 0.4 Mev and thus they must first be thermalized and then captured in cadmium. With the core operating at 50 Mw, the delayed neutron flux at the surface of the irradiator would be $10^{11} - 10^{12}$ n/cm²/sec. In order to limit the neutron flux at the surface of the meat to 10^4 n/cm²/sec a neutron shield of 42 cm of H₂O plus 1 mm of cadmium would be necessary. This shield would reduce the gamma flux by a factor of ~3. This effect is indicated in Section 4.1.5 page 43. The delayed neutron flux may be reduced by a factor of 10^3 with a five minute holdup of the core solution before utilization. This reduction in neutron flux will reduce the H₂O shield thickness to 24 cm. A 24 cm H₂O shield will reduce the gamma flux by a factor of 2.2. Thus the effective power of a reactor may be reduced by allowing delayed neutron decay, but significant additional costs would be required for the critically safe hold-up tanks.

Table 3.4 gives the costs of meat irradiation using the core solution from a large-scale power reactor (305 Mw core) with no delayed neutron decay. Two cases are considered. One using 20% of the available core power for an irradiation capacity of 40 tons beef/day to 2×10^6 rep, and the second using 100% of the core power which will irradiate 200 tons/day to 2×10^6 rep or 40 tons per day to 10^7 rep. The costs of these schemes, assuming no charge to irradiation facility for the reactor itself, are 1.47 cents/lb for 40 tons/day to 2×10^6 rep, 0.51 cents/lb for 200 tons/day to 2×10^6 rep, and 2.53 cents/lb for 40 tons/day to 10^7 rep.

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Table 3.4 Core Solution Utilization in Conjunction with A Large-Scale Power Station

	Capacity (Irradiation Level)	
	40 tons/day (2 x 10 ⁶ rep) (61 Mw necessary)	200 tons/day (2 x 10 ⁶ rep) 40 tons/day (10 ⁷ rep) (305 Mw necessary)
Core Solution Loop	\$ 25,000	\$ 65,000
Hot Cells	350,000	350,000
Irradiation Facility	163,000	278,000
Building and Site	<u>100,000</u>	<u>170,000</u>
Total Materials and Labor	\$ 638,000	\$ 863,000
30% Contingency	<u>191,000</u>	<u>259,000</u>
Subtotal	\$ 829,000	\$1,122,000
10% Engineering	82,900	112,200
45% Contractor	<u>373,000</u>	<u>505,000</u>
Total Cost	\$1,284,900	\$1,739,200
Fixed Charge, 15%	192,500	261,000
Operation and Maintenance (10 people)	100,000	100,000
Additional Inventory	<u>3,000</u>	<u>15,000</u>
Net Annual Operating Costs	\$ 305,500	\$ 526,000
Net cost per pound of meat, cents		
(2 x 10 ⁶ rep)	1.47	0.51
(10 ⁷ rep)	-	2.53

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Table 3.5 gives the cost of meat irradiation using the same reactor but this time allowing a 5 minute decay period for delayed neutrons. With this case, the capacity is increased to 290 tons/day at 2×10^6 rep and 60 tons/day at 10^7 rep. However, the unit costs are slightly higher than the previous case, these costs being 0.61 cents/lb and 3.05 cents/lb respectively.

3.5 Combined Utilization of Core Solution, Hydroclone Underflow, and Off-Gas from a Large Scale Homogeneous Power Reactor

The ultimate in meat irradiation would be the combined use of all available gamma radiation. Thus a homogeneous reactor, having a core power of 305 Mw, could be used to irradiate 530 tons of beef per day to 2×10^6 rep or 106 tons per day to 10^7 rep. Table 3.6 indicates the costs associated with such a scheme. These costs would be 0.28 cents/lb at 2×10^6 rep and 1.40 cents/lb at 10^7 rep.

The use of the core solution and the off-gas from a small homogeneous reactor in order to irradiate 40 tons beef per day to 2×10^6 rep would show very little cost advantage. (See Table 3.7) The reactor power would be 26 Mw, very small for economic power, and the cost would be 5.3 cents per pound of beef. This cost is still higher than the single purpose heterogeneous reactor cost.

3.6 Higher Irradiation and Facility Flexibility

As stated in the Introduction, it may be necessary, in some cases, to irradiate to 10^7 rep. This higher irradiation would either require a reduction in throughput or an increase in available reactor power. The available reactor power may be increased by using a larger fraction of the homogeneous core solution or off-gas streams as indicated previously for the cases of large-scale power reactors. However, an increase in reactor power or even a larger reactor would be necessary for the utilization of a single purpose reactor. Table 3.8 lists the costs associated with three different reactors for the single purpose of irradiating 40 tons of beef per day to 10^7 rep. Case one is a heterogeneous

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Table 3.5 Core Solution Utilization in Conjunction with A Large-Scale Power Station

(5 minutes decay of delayed neutrons; 305 Mw heat)

	290 tons/day
	(2×10^6 rep, or 60 tons/day at 10^7 rep)
Core Solution Loop	\$ 83,000
Hot Cells	350,000
Hold-Up Tanks and Cell	900,000
Irradiation Facility	318,000
Building and Site	<u>195,000</u>
Total Materials and Labor	\$1,846,000
30% Contingency	<u>554,000</u>
Subtotal	\$2,400,000
10% Engineering	240,000
45% Contractor	<u>1,080,000</u>
Total Cost	\$3,720,000
Fixed Charges, 15%	558,000
Operation and Maintenance (10 people)	100,000
Water, Power, etc.	75,000
Additional Inventory	<u>188,000</u>
Net Annual Operating Cost	\$ 921,000

Net Cost per pound of meat, cents (2×10^6 rep)	0.61
(10^7 rep)	3.05

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Table 3.6 Combined Utilization of Core Solution, Hydroclone Underflow, and Off-Gases in Conjunction with A Large-Scale Power Reactor

(305 Mw heat; capacity of off-gas section, 290 tons/day;
capacity of core solution loop section, 200 tons/day;
capacity of clone underflow section, 40 tons/day; total
capacity of 530 tons/day at 2×10^6 rep.)

Core-Solution Loop	\$ 65,000
Off-Gas Loop	83,000
Clone-Underflow Loop	25,000
Hot Cells	350,000
Irradiation Facility (3-part)	600,000
Building and Site	<u>235,000</u>
Total Materials and Labor	\$1,358,000
30% Contingency	<u>408,000</u>
Subtotal	\$1,766,000
10% Engineering	176,600
45% Contractor	<u>795,000</u>
Total Cost	\$2,737,600
Fixed Charges, 15%	410,000
Operation and Maintenance (20 people)	200,000
Water, Power, etc.	130,000
Additional Inventory	<u>15,000</u>
Net Annual Operating Cost	\$ 755,000

Net Cost per pound of meat, cents (2×10^6 rep)	0.28*
(106 tons to 10^7 rep)	1.40

(* Hypothetically, if the reactor charged the meat packers
1.8 cents per pound at a capacity of 530 tons/day at 2×10^6 rep,
power costs could be reduced from 7 mills/kwh to zero.)

Table 3.7 Combined Utilization of Core Solution and Off-Gas in Conjunction with A Small Power Reactor

(40 tons/day at 2×10^6 rep)

Reactor Equipment	\$ 230,000
Primary Coolant Loop	460,000
Steam Power Plant	750,000
Core Solution Loop	15,000
Off-Gas Loop	19,000
Miscellaneous	515,000
Irradiation Facility	200,000
Building and Site Development	<u>585,000</u>
Total Materials and Labor	\$2,774,000
30% Contingency	<u>831,000</u>
Subtotal	\$3,605,000
10% Engineering	361,000
45% Contractor	<u>1,622,000</u>
Total Cost	\$5,588,000
Land Only	<u>- 250,000</u>
	\$ 5,338,000
Total Adjusted Fuel Charges	221,000
Reactor Heat Power, Mw	26
Gross Thermal Efficiency	0.25
Power Plant Gross Capacity, Kw	6,500
Annual Credit Allotted to Plant Auxiliaries	27,000
Annual Credit Allotted to Mfg. Period Sales	91,400
Annual Credit Allotted to Off-Time	<u>37,800</u>
Total Annual Power Credit	\$ 156,200
Total Capital Cost, \$ (Depr. Items)	5,338,000
Total Capital Cost, Land	250,000
Annual Charges	
Fixed Charges, Land (12%)	30,000
Fixed Charges, (15% Depr. Items)	800,700
Fuel Charges	221,000
Operating and Maintenance (25% F.C.)	<u>200,200</u>
Total Annual Costs	\$ 1,251,900
Annual Power Credits	<u>156,200</u>
Net Annual Costs of Operation \$,	\$ 1,095,700
Net Cost/lb. of meat, cents	5.3

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Table 3.8

Reactor Costs for Irradiating 40 Tons of Beef per Day to 10^7 Rep

	Heterogeneous (Clean Core- Power)	Heterogeneous (Clean Core- No Power)	Homogeneous (D ₂ O Mod.- No Power)
Reactor Equipment	\$ 810,000	\$ 374,000	\$ 428,000
Primary Coolant Loop	1,050,000	733,000	933,000
Steam Power Plant	2,220,000	--	--
Blanket Loop	152,000	153,000	153,000
Miscellaneous	635,000	585,000	515,000
Irrad. Facility	220,000	220,000	220,000
Bldg & Site Develop.	655,000	585,000	585,000
Total Mat. & Labor	5,742,000	2,650,000	2,834,000
30% Contingency	1,722,000	795,000	850,000
Subtotal	7,464,000	3,445,000	3,684,000
10% Engineering	746,400	344,500	368,400
45% Contractor	3,360,000	1,552,000	1,660,000
Total Cost	11,570,400	5,341,500	5,712,400
Land Only	- 250,000	- 250,000	- 250,000
Net Cost	\$11,320,400	\$5,091,500	\$5,462,400

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	Heterogeneous (Clean Core- Power)	Heterogeneous (Clean Core- No Power)	Homogeneous (D ₂ O Mod.- No Power)
Total Adjusted Fuel Charges	\$ 2,295,000	\$ 1,060,000	\$ 790,000
Reactor Heat Power, Mw	155	85	82.5
Gross Thermal Efficiency	0.25	0.25	0.25
Power Plant Gross Capacity, Kw	38,750	21,300	20,625
Annual Credit Allotted to Plant Auxiliaries	161,000	--	--
Annual Credit Allotted to Mfg. Period Sales	545,000	--	--
Annual Credit Allotted to Off-Time	225,500	--	--
Total Annual Power Credit or Debit	931,500	- 96,500	- 93,500
Total Capital Costs, \$ (Depr. Items)	11,320,400	5,091,500	5,462,400
Total Capital Cost, Land	250,000	250,000	250,000
Annual Charges			
Fixed Charges, Land (12%)	30,000	30,000	30,000
Fixed Charges, (15% Depr. Items)	1,700,000	764,000	820,000
Fuel Charges	2,295,000	1,060,000	790,000
Operating and Maintenance (25% F.C.)	432,000	198,500	212,000
Total Annual Costs	4,457,000	2,052,500	1,852,000
Annual Debits	--	96,500	93,500
Annual Power Credits	931,500	--	--
Net Annual Costs of Operating, \$	3,525,500	2,149,000	1,945,500
Net Cost/lb of meat, cents	17.0	10.3	9.3

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clean core power reactor which has an irradiation cost of 17.0 cents/lb. Case two is a clean core heterogeneous reactor - no power which has an irradiation cost of 10.3 cents/lb. Case three is a D_2O - moderated homogeneous two-region reactor which has an irradiation cost of 9.3 cents/lb. In all cases an indium sulfate blanket is used as the irradiation medium.

Some flexibility can be designed into the irradiation facility in order to accomplish irradiation below 2×10^6 rep. The irradiation facility described elsewhere in this report uses a 100 minute irradiation time. Thus the irradiation level may be reduced to 2×10^5 rep by decreasing the irradiation time to 10 minutes. The throughput could thus be increased by a factor of 10 with a corresponding reduction in unit costs. This 10 minute irradiation time is probably the shortest period that could be used and 2×10^5 rep is the lowest irradiation level that could be accomplished by time control of the single monorail system alone. Irradiation below 2×10^5 rep could be accomplished by moving the meat packages a greater distance from the source, using a second monorail system, a lower indium sulfate concentration in the case of the blanket systems, utilization of a smaller fraction of the reactor off-gas, core solution, or hydroclone underflow, or by placing lead sheets between the source and the packages. Thus in all the above cases the reduction in the irradiation level is accomplished by a reduction in either/or all efficiencies - production, volume or utilization. For this reason the unit cost for irradiation to 2×10^5 rep and a ten minute irradiation time would be the minimum cost for all irradiations below 2×10^5 rep unless the irradiation time could be decreased and the throughput increased. Further study of the design of irradiation facilities and meat handling methods should be made in order to increase the throughput and decrease the unit cost for these low irradiations. These lower irradiations could best be accomplished with Co^{60} or Cs^{137} sources if these isotopes were available at low cost.

Table 3.9 Combined Utilization of Core Solution, Off-Gas, and Indium Sulfate Solution (10.5 Mw Reactor)

(40 tons/day at 2×10^6 rep)

Reactor Equipment	\$240,000
Primary Coolant Loop	270,000
Core Solution Loop	15,000
Off-Gas Loop	19,000
Blanket Loop	44,000
Miscellaneous	515,000
Irradiation Facility	230,000
Building and Site Development	585,000
Total Materials and Labor	1,918,000
30% Contingency	576,000
Subtotal	2,494,000
10% Engineering	249,400
45% Contractor	1,122,000
Total Cost	3,865,400
Land Only	- 250,000
	3,615,400
Total Adjusted Fuel Charges	124,000
Reactor Heat Power, Mw	10.5
Gross Thermal Efficiency	0.25
Power Plant Gross Capacity, Kw	2,630
Total Annual Power Debit	- 12,000
Total Capital Cost, \$ (Depr. Items)	3,615,400
Total Capital Cost, Land	250,000
Annual Charges	
Fixed Charges, Land (12%)	30,000
Fixed Charges, (15% Depr. Items)	542,000
Fuel Charges	124,000
Operating and Maintenance (25% F. C.)	143,000
Total Annual Costs	839,000
Annual Power Debits	12,000
Net Annual Costs of Operation, \$	851,000
Net Cost/lb. of Meat, Cents	4.1

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Lower irradiations, $\sim 10^4$ rep, to materials other than meat could be accomplished with a chute or hopper with variable feed to vary the effective residence time in the irradiation field from 30 seconds to 10 minutes. In some cases an extra monorail or fast traveling belt could be added in parallel to the monorail for meat packages in order to give a shorter irradiation time for other package foods.

3.7 Combined Utilization of Core Solution, Off-Gas, and Indium Sulfate Solution (10.5 Mw Reactor)

Another possibility for a food irradiation system might involve a small homogeneous reactor in which the combination of core solution, off-gas, and indium sulfate could be utilized as sources. The unit cost for such a system has been estimated at 4.1 cents per pound of meat. See Table 3.9. The reactor would be a two-region, D_2O moderated, homogeneous type utilizing an indium sulfate solution blanket. One complication of this system, e.g. as compared with Case 3 in Table 3.2, would be that the irradiation facility requires the use of three irradiation sources, i.e. one each for the core solution, off-gas system, and the activated indium sulfate solution. Two additional irradiation sources might possibly be considered, i.e. (1) hydroclone underflow and (2) off-gas charcoal beds. These were not considered because (1) the hydroclone system would increase the meat throughput only about 3% and (2) the distribution of activity through the charcoal beds would be non-uniform.

The cost of this system at 4.1 cents/lb compares favorably with the 4.7 cents/lb for the single-purpose indium sulfate solution reactor and the 5.3 cents/lb for a small reactor using off-gas and core solution sources.

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3.8 Cost of Meat Irradiation Using Cobalt-60

One alternative to the use of a reactor to supply gamma irradiation would be the use of either Co^{60} or Cs^{137} . Cobalt-60 would be reactor-produced and would probably have a projected cost of \$0.50/curie. Cesium-137, which has only 1/4 the total gamma energy per beta disintegration of Co^{60} , would have to carry a cost of \$0.125/curie in order to be competitive. This cost is very probable in the future, but at present there will not even be enough separated cesium to supply the requirements for one irradiation facility. On the other hand, some of the reactor space at Hanford or Savannah River could be turned over to Co^{60} production with a loss in plutonium production. Therefore, Co^{60} was assumed to be the basis of comparison with the reactor cases.

Table 3.9 lists the cost of a Co^{60} irradiation facility which will irradiate 40 tons of beef per day to 2×10^6 rep. The cost of the sources considered were \$0.50, 1.00, 2.00, and 5.00 per curie. The net cost per pound of meat irradiated to this level for the above source costs would be 2.8, 4.0, 6.4, and 13.5 cents respectively. Thus it may be seen that the irradiation of beef using a Co^{60} source at \$1.00/curie is more economical than a no-power reactor with irradiations up to 2×10^6 rep. However, for meat irradiations to 10^7 rep the use of a two-region homogeneous reactor as an irradiation source becomes more economical than Co^{60} if the cost of Co^{60} is greater than \$0.60 per curie. This value was obtained by considering the cost of the new source, the burnup of Co^{60} and a slight increase in the cost of the irradiation facility (to \$200,000). The cost of irradiating 40 tons of beef per day to 10^7 rep using cobalt sources which cost \$0.50, 1.00, 2.00, and 5.00 per curie would be 7.6, 13.5, 25.3, and 60.7 cents per pound respectively. The corresponding irradiation cost for the two-region homogeneous reactor would be 9.3 cents per pound. (See Table 3.8).

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Table 3.10

Cost of Meat Irradiation Using Cobalt-60

<u>Item</u>	<u>Cost, \$ or \$/yr</u>
Co ⁶⁰ -Source (Initial Capital Investment--\$0.50/curie)	\$ 900,000
Cooling System for Source	10,000
Instruments	20,000
Irradiation Facility	163,000
Manipulation and Control of Source	50,000
Building and Site Development	460,000
Total Materials and Labor	\$1,603,000
30% Contingency (Total -- Source)	210,900
Subtotal	\$1,813,900
10% Engineering (Subtotal -- Source)	91,400
45% Contractor (Subtotal -- Source)	411,300
Total Cost	\$2,316,600
Land Only	- 125,000
Net Capital Cost	\$2,191,600
Fixed Charges, \$/yr	
15% of Capital	328,800
12% of Land	15,000
Operation and Maintenance	120,200
Cobalt-60 Replacement	110,400
Power Used	15,000
Net Annual Cost, \$/yr	\$ 589,400
Net cost per pound meat, cents	2.8
Net cost per pound meat, cents (\$1.00/curie)	4.0
Net cost per pound meat, cents (\$2.00/curie)	6.4
Net cost per pound meat, cents (\$5.00/curie)	13.5

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4.0 APPENDIX

4.1 Background of the ORSORT Study (2)

The choice of a "Food Sterilization Reactor" as the subject of an ORSORT summer problem resulted from a suggestion by the Quartermaster Corps in association with the Army Reactors Branch of the AEC. According to Colonel W. D. Jackson, chief of the research and development division of the U. S. Army's office of the Quartermaster General⁽³⁾ there are three ways in which benefit may be obtained if radiation processing of food proves practical:

1. Reduction of shipping cost for large quantities of meat sent to armed forces overseas. The shipping cost from Chicago to Tokyo is 8.7 cents/lb for frozen meat and 3 cents for nonperishables.
2. Radiation processing (rendering meat nonperishable) could relieve the congestion of machinery-laden Naval vessels and eliminate the expense of static refrigeration facilities.
3. Reduction in the frequency of resupplying warships with perishables would increase their cruising range.

In general, it is believed that shelf life of some foods will be improved, that refrigeration costs and food losses will be reduced.

About 1952, the Quartermaster Corps began a five-year plan with its goal — sufficient demonstrated progress toward practical irradiation sterilization to induce industry to step in. Completion of the necessary development work to establish a food processing industry based upon irradiation sterilization would then be the responsibility of private industry.

By early 1955 the technology of food irradiation was sufficiently developed to indicate considerable promise. Irradiated food had been submitted to the Surgeon General for Toxicity tests. Animal feeding tests were being made and human feeding experiments were planned. At this time the Quartermaster Corps, in association with the Army Reactors Branch of the AEC, decided to undertake a food sterilization reactor feasibility study.

4.1.1 Bases and Objectives of the Study

The problem was defined to consist of the choice, conceptual design and evaluation of a reactor-irradiation system capable of meeting the following requirements:

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1. Capacity 40 tons (80,000 lbs) per day
2. Operating Time 10 hours per day, 5 days per week
3. Shutdown Time - weekends
4. Size of Irradiated Packages
No. 2 and No. 10 cans
Cartons 6" x 16" x 20" (size normally used to ship meat cuts)
5. Conveyor System - Automatic
6. Processing Time for Irradiation - 5 to 10 minutes
7. Dose - 2,000,000 rep.
8. Dose Variation -- 0% to + 25%

Reactor reliability and freedom from operating difficulties were stated to be of prime importance. For purposes of cost estimation a Chicago location was specified. It was assumed that a processing cost of 2 - 5 cents per pound be presented, a cost against which the promise of the design could be measured.

4.1.2 Conclusions and Recommendations of ORSORT Study

4.1.2a Feasibility of Meat Processing with Reactor Produced Gamma Radiation

Several conclusions may be made about sterilization with reactor produced gamma radiation:

1. Beef processing with reactor produced gamma radiation is feasible and will satisfy all of the specifications^a written by the Quartermaster Corps and listed in section 1.0 . It should be noted that limits on odor and taste changes are not included in these specifications. It is generally believed, however, that food technology developments will adequately control these changes.

2. The scope of work in this study does not permit the selection of an optimum reactor-irradiation system. It is concluded that each of several

^aA longer processing time than 10 minutes may be required -- it is believed that this will not affect processing results obtained.

reactor types may be satisfactorily coupled to an irradiation facility. Further work would be required to select the best of these types.

3. Processing with reactor produced gamma radiation is less expensive than the use of radiation from other sources. Dose variation is more readily controlled than when beta rays are used.

4.1.2b Processing with Coolant Activated in Core or Blanket of Heterogeneous Reactor

A satisfactory way of producing gamma radiation and applying it to processing of beef is to activate a coolant passing through the core or blanket of a heterogeneous reactor. For this reactor-irradiation system the following additional and detailed conclusions can be made:

1. Intermittent operation (5, 10 hour days per week) of the system and "dumping" the heat produced within the reactor results in an estimated processing cost of 3.1 cents/pound of beef. Total capital investment required is \$2,300,000.

2. Continuous operation (0.80 "on-stream" factor) permits a smaller required capital investment. Processing cost for this case is 1.7 cents/pound beef. Total capital investment required is \$1,270,000.

3. Addition of power production facilities was considered. Credits obtained for power produced do not offset the necessary charges for additional capital investment.

4. A processing time of ten minutes is difficult to obtain with reactor produced radiation. Cost estimates quoted in conclusions 1 and 2 above are based upon a 100 minute processing time. Shorter times are possible with a small penalty in processing costs.

In intermittent operation (conclusion 1)

Processing Time, Minutes	100	55
Total Capital Investment, \$	2,300,000	2,262,000
Processing cost, cents/lb	3.1	3.5

5. Operation with a "clean" core and with activation in the blanket is preferable to "dirty" core operation with activation in the reactor core.

The area of chief concern and one requiring further thought is the chemical and radiological stability of the aqueous solution to be activated.

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The conclusions above are based in large part upon results obtained for a neutron activated solution of indium sulfate.

4.1.2c Recommendations for Future Work

1. With the objective of possible reduction of processing costs below those stated in this report, it is recommended that other reactor-irradiation systems be designed and cost estimated. Examples of such systems are:

a. Use of D_2O in Heterogeneous or Homogeneous core, with an activated blanket.

b. Activation of indium coated belt passing through water outside reactor core and thence to the irradiation facility.

2. An investigation of the chemical and radiological problems associated with the use of an indium sulfate solution should be made.

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4.1.3 Irradiation Facilities

The following section describes the irradiation facility that would be used for the induced activity system. This description was obtained entirely from ORNL CF 55-8-190, "Reactor Design and Feasibility Problem: A Food Sterilization Reactor."⁽²⁾ This type of facility, although designed for use with a heterogeneous reactor with indium sulfate solution blanket, can be used with a homogeneous reactor with the same solution blanket.

ORNL CF 55-8-190 should be consulted for greater detail of design calculations and methods used in establishing the most feasible design.

Introduction

The specifications of the irradiation facility are based on the general requirements laid down by the U. S. Quartermaster Corps. For sterilization of meat and meat products (beef) a best dose value was set at about 2 million rep deposition and in addition this dose must be uniform within the limits of 2 and 2.50 million rep. A processing rate of 40 tons per 10-hour day and a maximum holdup time of 10 minutes fix the processing volume at 600 liters. The size of the individual packages used for this design are those cartons with dimensions 6" by 16" by 20".

Geometry of the Source Volume and Processing Line

For reasons of mechanical simplicity and minimum source self-absorption a rectangular slab shaped volume was chosen for the source irradiation volume. Cylindrical and spherical geometries offer less exposure surface per unit volume and more self-absorption per unit volume than an equal volume rectangular geometry. A qualitative disadvantage to the rectangular system is the edge effect which involves not only non-uniformity of dose but high leakage of photons out the ends and sides of the slab.

The 6" by 16" by 20" cartons and the rectangular slab source about which the processing line is built determine the best geometry for the process line. Using the methods of Straight Ahead Scattering of Photons (NYO-3075), the heating up or energy deposition in the meat was calculated as a function of penetration depth. Based on these results the cartons

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must pass the irradiation volume single file and with each of the two sides in turn closest to the source in order to keep the dose within the specified 25% overdose.

Effect of Specific Activity of Source and Processing Time on Volume of Irradiation Source

The required dose, the process volume, and the dose variations determine the required surface strength of the source volume. The required specific activity (disintegrations/sec/cm³) is then determined for various source thicknesses. A so-called two-pass system is taken to be the optimum, the utilization being determined by both the stopping power of the meat and the hold-up time required to make each pass.

A variation in dose occurs due to an edge effect in the meat and source slab. This variation in dose is calculated as a function of source slab overlap on the sides of the conveyor for different distances of meat from source. The solution is obtained graphically for a number of cases.

$$\tan^{-1} \frac{l'}{Z} = \frac{K}{2} \left[\tan^{-1} \frac{l' + l}{Z} + \tan^{-1} \frac{l' - l}{Z} \right] \quad \text{Eq. 7-1}$$

Z = distance between source and meat

l' = source half-width

K = (1 + variation in dose)

l = meat coverage half-width

Since the surface strength of the source depends on thickness as well as specific volume activity, the fraction of total source activity leaking out of one face of a slab source can be plotted.

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$$\frac{\sigma_o}{S_o t} = \frac{1}{2\mu t} \left\{ 0.5 - E_3^P(\mu a) - E_3^P(\mu t) + E_3^P(\mu \sqrt{t^2 + a^2}) \right\} \quad \text{Eq. 7-2}^*$$

σ_o = surface source strength

t = source thickness

E_3^P = See Placzek Functions **

S_o = volume source strength

a = source radius

Combining these results with those on the edge effect, one obtains a relationship (partially empirical) between S_o , the specific volume activity required and V_{ir} , the volume of the irradiation source. The results are tabulated in Table 4.1

$$V_{ir} = A \text{ meat } \left(1 + \frac{L}{40}\right)t$$

$$S_o = \frac{\sigma_o}{t} \frac{1}{(\sigma_o/S_o t)} \quad \text{Eq. 7-3}$$

V_{ir} = irradiation volume

L = overlap of source

A = meat area

t = source thickness

σ_o = surface source strength

* Can be shown using methods in NYO-3075 and CF 54-10-76.

**N. R. C. No. 1547, The Functions $E_n(x) = \int_0^\infty e^{-xu} u^{-n} du$, G. Placzek.

$$\frac{V_{ir}^{10}}{\tau} = A_{meat} \left(1 + \frac{L}{40}\right) \frac{\sigma_o}{\tau_{S_o} \left(\frac{\sigma_o}{S_o t}\right)} \quad \text{Eq. 7-4}$$

τ = holdup time in minutes

L = overlap

$(\sigma_o/S_o t)$ = from Fig. 7-4

In order to compare the utilization of the gamma energy at different activity levels, Table 4.2 was prepared with the utilization, U , obtained from:

$$U = \frac{\text{theoretical dose}}{S_o V_{irr}} \quad \text{Eq. 7-5}$$

Mechanical Design of Source Volume and Food Carrier

The design of the source volume is based on the assumptions made earlier. For a 10 minute processing time and arrangement as shown in Fig. 4.1, the source volume is taken to be 5' x 6' x 1' rectangular stainless steel tank with appropriate inlet and outlet connections to control the flow rate. The food carrier consists of a simple monorail system which seems to best fit the processing rate and weight flow through the system. The decision on the monorail system was reached after preliminary discussions with a number of conveyor engineering companies. A plan view of the system including shielding is shown in Figure 4.2. The configuration used in Figure 4.2 is based upon the plan shown in Nuclear Engineering - Part III, "Design of a Pork-Irradiation Facility Using Gamma Rays to Break the Trichinosis Cycle", H. J. Gomberg, et al.

Shielding and Refrigeration of Irradiation Facility

Using $S_o = 10^{13} \frac{\text{decays}}{\text{cm}^3 \text{-sec}}$ the source strengths for each gamma energy from activated indium is calculated and these in turn used to find the thickness of concrete shielding required to reduce the dose immediately outside the 0.1 mr/hr. It is found by standard shielding calculations,⁽¹⁾

⁽¹⁾ See Apex 176

Table 4.1

Relationship Between Specific Activity and Volume of Source

Passes	t (cm) Source Thickness	V(liters) Source Volume	$S_0 \frac{\text{mev}}{\text{cm}^3 \text{ sec}}$ Specific Activity
1	1	60	11.6×10^{12}
	2	120	6.2
	3	180	4.38
	5	300	2.90
	10	600	1.79
	20	1400	1.22
	30	2100	1.03
2	1	30	15.9×10^{12}
	2	60	8.4
	3	90	6.0
	5	150	4.0
	10	300	2.44
	20	700	1.66
	30	1050	1.41
3	1	20	20.5×10^{12}
	2	40	10.8
	3	60	7.65
	5	100	5.06
	10	200	3.14
	20	467	2.15
	30	700	1.82
	40	1067	1.66

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Table 4.2

Efficiency of Source Utilization as Function of
Its Specific Activity and Volume

Passes	t_s (cm)	V_s liters	$S_o \frac{\text{mev}}{\text{cm}^3 \text{ sec}}$	$S_o V_s$	Utilization (%)
1	1	60	11.6×10^{12}	6.9×10^{17}	15
	2	120	6.2	7.42	14.0
	3	180	4.38	7.88	13.2
	5	300	2.90	8.7	11.9
	10	600	1.79	10.8	9.7
	20	1400	1.22	17.1	6.1
	30	2100	1.03	21.6	4.8
2	1	30	15.9×10^{12}	4.77×10^{17}	21.7
	2	60	8.4	5.03	20.6
	3	90	6.0	5.40	19.2
	5	150	4.0	6.00	17.3
	10	300	2.44	7.32	14.2
	20	700	1.66	11.67	8.9
	30	1050	1.41	14.8	7.0
3	1	20	20.5×10^{12}	4.1×10^{17}	25.4
	2	40	10.8	4.32	24.0
	3	60	7.65	4.58	22.7
	5	100	5.06	5.06	20.5
	10	200	3.14	6.28	16.6
	20	467	2.15	10.0	10.4
	30	700	1.82	12.8	8.1
	40	1067	1.66	17.8	5.8

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FIG. 4.1

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SELECTED GEOMETRICAL ARRANGEMENT
OF SOURCE & PROCESS LINES
(NOT - TO - SCALE)

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Fig. 4.2

ORNL-IR-DWG.-10279
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PLAN VIEW
10 MIN. IRRADIATION FACILITY

using buildup factors, that 5 feet of barytes concrete is needed. The geometry of the shield chosen is illustrated in Fig. 4.2.

In order to preserve the natural taste of beef, it is best to irradiate while frozen. (a) The frozen food may gain heat by both gamma-ray heating and convection heating while in the proximity of the source volume. Using a process rate of 40 tons per 10 hour day at a dose level of 2 meg. rep., the gamma-heating amounts to 5.7×10^4 BTU/hr. Using a heat transfer coefficient of 10 and ΔT of 40°F the sensible heat transferred from the room amounts to 4.8×10^4 BTU/hr giving a total of 1.05×10^5 BTU/hr as compared to 1.15×10^6 BTU/hr required for the heat of fusion. It follows that:

$$\frac{1.05 \times 10^5 \text{ BTU/hr}}{1.15 \times 10^6 \text{ BTU/hr}} = \text{fraction of meat thawed at } 32^\circ\text{F} = 9.1\%$$

$$9.1\% \times 144 \text{ BTU/lb} = 13 \text{ BTU/lb (if } C_p = 1)$$

This means that the frozen beef must enter an unrefrigerated irradiation facility at 19°F to prevent any thawing during irradiation. If it is chosen to refrigerate the irradiation facility then the meat gains heat only by gamma heating. This amounts to:

$$\frac{5.7 \times 10^4}{1.15 \times 10^6} = 5\% \text{ thawing at } 32^\circ\text{F}$$

$$5\% \times 144 \text{ BTU/lb} = 7.2 \text{ BTU/lb}$$

This means that the irradiation facility must be refrigerated to 27°F to prevent any thawing of the processed beef.

Assuming a 100°F temperature drop across the 5 foot concrete wall the heat removal was calculated and resulted in a refrigeration capacity of 4.1 tons for the 9' x 57' x 30' overall irradiation cell. The capacity need not be this high if, as is likely, a larger refrigerated storage room surrounds the irradiation cell.

Economics of the Irradiation System (See Tables 4.3 and 4.4)

Concrete Shielding and Housing

The amount of concrete used in the shielding and cell construction is as shown in Fig. 4.2 with the calculated amount equal to 494 cubic yards.

(a) U. S. Quartermaster Corps (private communication)

The installation of the concrete was figured at two extremes, \$50 and \$120 per cubic yard.^(a) Excavation for the facility was estimated to be 232 yards³ at \$2.70/yd. The total cost is shown in Table 4.3.

Conveyor Cost^(a)

Using an article in "Nuclear Engineering," AICHE, and after preliminary discussion with a number of conveyor engineering firms a value was estimated for the conveyor system. Using a value of 190 feet for monorail length, a total cost per foot was calculated.

Source Slab

Based on a cost of \$5/lb for fabricated and installed stainless steel, a value was arrived at for the cost of 5' x 6' x 1', 1/5" thick tank.

Refrigeration Costs^(a)

These costs were based on a value of \$400/ton capacity required.

Table 4.3

Estimated Cost for 10 Minute Irradiation Facility

	<u>Part at \$120 yd.</u>	<u>At \$50 yd.</u>
Total Concrete	\$ 86,500	\$63,600
Excavation	620	21,490
Conveyor in Irradiation Cell	2,220	
Conveyor Outside of the Cell	1,980	
Source Container	2,650	
Refrigeration Equipment	1,950	
Source Duct into Cell	1,500	
Monitoring Equipment	5,100	
Ventilation	1,920	
Access Doors	1,540	
Mis. labor (wiring, piping, etc.)	2,000	
Total	\$107,990	\$84,790

^(a) Nuclear Engineering - Part III (page 89) Chemical Engineering Symposium Series, No. 11, 1954 (Vol. 50)

Table 4.4

Summary of Incremental Costs for Increase in Size of Irradiation Facility

Hold-Up Time (Min.)	Source Slab Length (Ft.)	Slab Length	Incr. Cost Over 10 Minute Facility	
			Concrete (a) \$120/yd.	Concrete (a) \$50/yd.
10	2.5	0	--	--
20	5.0	2.5	6,050	4,400
30	7.5	5.0	12,100	8,800
60	15.0	12.5	30,100	22,000
80	20.0	17.5	42,300	30,800
100	25.0	22.5	54,400	39,600

4.1.4 Selection of the Coolant to be Activated in the Reactor

In order to make a selection of a suitable nuclide which could be neutron-activated within the reactor, a chart of nuclides was studied. A selection of several nuclides, which, upon absorption of a neutron would decay with emission of gamma radiations of high energy was made.

After making these selections several additional criteria were established to use in choosing nuclides to be further considered. These criteria are:

(a) Isotopic abundance

No isotopic separation should be required to make the nuclide available in usable form.

(b) Nuclear cross section

The minimum thermal neutron absorption cross section should be one barn.

(c) Product half-life

The half-life of the active nuclide created by neutron capture should be (a) long compared to "travel" time around the active loop, and (b) short enough to allow access to the active loop and irradiation facility after approximately 24 hours.

Table 4.5 lists the nuclides which meet the criteria established.

At the irradiation facility the gamma ray utilization will be improved by the use of an aqueous medium rather than a non-aqueous medium such as liquid metal or fused salt. Self-shielding losses in the source will be much smaller. Thus water-soluble salts of the nuclides listed have received particular attention. Bromides are, in general, quite soluble and would make possible high macroscopic cross sections for neutron capture. However, bromides are unstable to radiation and in addition, inhibit the recombination of radiation decomposed water. Sulfates, in general, are quite soluble (less soluble than the bromides) and are radiation stable.

After a study of the listed nuclides and their salts, the sulfates of manganese and indium were selected as the salts upon which further design work would be based. For this work the solubility of both indium

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and manganese sulfates was taken at a value somewhat lower than the lowest solubility within the expected operating temperature range. (a) For manganese sulfate it was taken as 0.30 grams per cubic centimeter; for indium sulfate, 0.5 grams per cubic centimeter of solution. The corresponding macroscopic thermal neutron absorption cross sections are 0.0155 cm^{-1} for capture in manganese and 0.173 cm^{-1} for capture in indium. These values have been used to fix a range of cross sections used in ORACLE calculations for the reactor core. These calculations are described in a later section of the report.

Some estimated costs for the several nuclides are listed in Table Except for gallium and perhaps lanthanum and praseodymium, cost is not an important factor bearing upon the choice of nuclide.

(a) "Solubilities of Inorganic and Organic Compounds" Supplement to the Third Edition, D. Van Nostrand Co., New York, N. Y., Page 361 (1952).

Table 4.5

Nuclides Suitable for Activation for Irradiation Facility

Element	Symbol	Isotope	Percent Abundance	Cross Section (barns)	Product Half-life	Gamma Energy (Mev)	%	Cost (\$/lb)
Antimony	Sb	121	51	6.8	2.8d	0.57	24 8 6 70 95 0.05	0.20
		123	43	2.5	60 d	0.7 0.65 2.06 1.70 0.60 23		
Arsenic	As	75	100	4.9	26.8h	2.1 1.8 1.25 0.57	7 weak ~19 ~19	0.70
Bromine	Br	79	51	8.9	4.4h	0.049 0.037 0.547 1.7-2.0 1.35 0.787	100 100 ~100 0.14 ~100 ~100	---
		81	49	2.3	35.5h			
Copper	Cu	63	69	2.8	12.8h 4.3M	1.34 ---	(k capture) ---	0.30
Gallium	Ga	69	60	1.5	20 m	---	--- weak ~100 54 5 15 weak 33	1360.
		71	40	3.4	14 h	1.47 0.83 0.631 0.69 1.05 1.57 2.18		

Element	Symbol	Isotope	Percent Abundance	Cross Section (barns)	Product Half-life	Gamma Energy (Mev)	%	Cost (\$/lb)
Indium	In	113	4	56 b	50 d	0.192	97	33..
						0.715	3	
		115	96	145	54 m	0.548	3	
						1.487	21	
						0.406	25	
						2.090	25	
						1.085	54	
						1.274	75	
Lanthanum	La	139	100	8.4	40 h	2.5	4	
						1.6	74	
						0.82	15	
						0.49	5	
						0.335	1	
Manganese	Mn	55	100	13	2.6h	3.13	12.5	0.32
						0.81	18.75	
						0.845	69	
Scandium	Sc	45	100	22	85 d	1.12	98	
						0.89	98	

4.1.5 Choice of Reactor - Irradiation System

Introductory Remarks

Criteria for Choice

The type of reactor to be designed by the ORSORT group was not stated in the specifications written by the Quartermaster Corps. The choice of reactor type thus became the responsibility of the design group and represented the first major decision. In order to make this decision, a preliminary evaluation of several reactor types was made. Several broad criteria were used. Stated as questions, these are:

- (1) Does the proposed system make use of existing reactor technology or are there technical difficulties requiring long-term development?
- (2) Is the system simple, trouble-free and capable of operation without unscheduled shutdown?
- (3) What is the relative power level of the reactor?

The answer to the final question is, for some designs very largely inherent in the ability of the design to utilize the forms of gamma radiation created by fission. According to Glasstone and Edlund, ^(a) from a total fission energy of 195 Mev, the following amounts of gamma ray energy are available:

Gamma decay energy,	5 Mev
Instantaneous gamma-ray energy,	6 Mev

Other designs may make available gamma radiation from decay of radioactive isotopes created by neutron capture. Assuming one capture per fission and a gamma decay strength of 2 Mev, the gamma energy available in such a design is 2 Mev per fission. Thus there is an efficiency, which we may call a production efficiency, which describes the maximum amount of gamma energy associated with 195 Mev of energy/fission.

Other efficiencies are recognized. These are:

- (1) A volume efficiency. This exists because in most designs the gamma strength cannot be used where it is created but must be divided between a point of creation and point of use.

(a) Glasstone and Edlund, "The Elements of Nuclear Reactor Theory" Van Nostrand, 1952. p 71, Table 4.23.

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(2) A utilization efficiency. In the irradiation facility, losses occur due to self attenuation of gamma rays within the source, failure to intercept gamma rays with meat and leakage of gamma rays (unattenuated) through the meat.

Limits of Neutron Exposure

Before discussing particular reactor designs, it should be noted that in addition to the above broad evaluation criteria, a specific requirement is imposed by food technology requirements. This requirement is that excessive neutron exposure be avoided. Neutron exposure is excessive if the processed food possesses any measurable activity 20 min after exposure, if the flavor of the food is spoiled or if particular isotopes (Ca^{45} or Trit for example) are produced in excess of body tolerance. The amount of neutron exposure which will spoil the flavor of food is poorly defined. Technological developments, however, indicate that these flavor changes may be controlled to permit higher thermal neutron exposures.

A calculation was made of the permissible neutron flux to which beef could be exposed. The value of this flux was 1×10^4 neutrons/cm²/sec and was based on the following assumptions:

- (a) No measurable activity 20 min after exposure,
- (b) Ten-minute exposure time,
- (c) An assumed counting ability of 0.01 disintegrations/sec/cm³, and
- (d) An analysis of beef as reported in the American Scientist 40, 404 (1952).

Using body tolerance for particular isotopes as the limiting criterion, others ^(a) have estimated permissible thermal neutron flux of about 10^5 neutrons/cm²/sec for periods up to a half hour.

Use of Direct Fission Gammas and Decay Gammas from a Heterogeneous Reactor Core

Any reactor-irradiation system employing a heterogeneous reactor core possesses the following general advantages:

^(a) Lt. Colonel Belmont Evans, USQMC, Private Communication.

- (1) The reactor technology is proven,
- (2) No local fuel processing is required (would free meat packers of this responsibility), and
- (3) Activity is confined and the danger of loss of activity to the surroundings is minimized.

Using gamma strength directly from the reactor core maximizes both the production and volume efficiencies and promises, therefore, a reactor of minimum power. Unfortunately, however, the gamma strength available is intimately associated with a high neutron flux. The upper limit set upon thermal neutron exposure dictates that a discriminating shield (one to separate neutrons from gamma rays) be built between the reactor core and the irradiation facility. Water is such a shield and a good one. However, the neutron flux is reduced to the permissible level only after a large attenuation of gamma rays has also occurred. For this proposed method of design the utilization efficiency is extremely low.

Assuming a permissible thermal neutron flux of 1.0×10^4 neutrons/sec/cm² at the shield surface the following thicknesses of water shield would be required for the Bulk Shielding Facility operating at several power levels.

<u>Power Level</u>	<u>Water Shield Thickness, cms</u>
1 kw	85
1 mw	140
1 mw (hypothetical)	165

For these shield thicknesses the corresponding gamma doses are:

<u>Power Level</u>	<u>Gamma Dose, Rep/hour</u>
1 kw	112
1 mw	6,720
10 mw	33,600

To process beef in 10 min, a dose of 2×10^6 rep requires 1.2×10^7 rep/hour. Thus, attenuation in the shield is seen to be prohibitively large.

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A proposal to use a "capture" plate at the end of the water shield, to create capture gammas by neutron absorption, proved unpromising. The neutron flux has been largely reduced by the water shield required. Placing the atoms to be activated in the water shield itself as a soluble salt was considered. In this case, attenuation of the capture gammas in the water shield was too large.

Estimated power for this design is:

$$P = 0.0167 \times \frac{195}{11} \times 1 \times \frac{1}{0.001} = 296 \text{ mw.}$$

theoretical
production
volume
utilization
power
efficiency
efficiency
efficiency

A Heterogeneous Reactor Operated Intermittently

This system would use a heterogeneous reactor core operated only at night or on weekends. During other hours the core would be used as a gamma radiator for meat processing. By this method of operation exposure to neutrons is avoided. At the same time the full gamma decay strength of the core is used.

The system is fully compatible with existing technology, and there are no obvious technical difficulties which would prevent rapid development. Intermittent operation, however, brings about use of a decaying and therefore unsteady irradiation field. The degree of decay of the field during food processing can be reduced by the use of appreciably burned up fuel elements whose saturated activity is approached (Apex-134). If saturated activity were reached when the reactor were shut down, a decay of 22% in gamma strength would occur in 10 hrs.

Other disadvantages are:

- (1) The operating procedure would inherently be too rigid to permit any changes in production schedules,
- (2) Mechanical difficulties arising from the fact that the food conveyor mechanism would, by necessity, be located in a high neutron field when the reactor is operating, and
- (3) Self-shielding of the fuel elements considerably reduces the efficiency of utilization of the gamma radiation.

Estimated power requirement for this design is:

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$$P = 0.0167 \times \frac{195}{5} \times \frac{1}{0.5} \times \frac{0}{0.05} = 26 \text{ mw.}$$

theoretical power	production efficiency	time efficiency, core used as gamma radiator 1/2 of time	utilization efficiency
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Use of Gaseous Fission Products from a Homogeneous Reactor

In this proposed operation, gaseous fission products from a homogeneous reactor core would be absorbed on beds of charcoal (or other absorbent). Decay of these fission products would supply the gamma radiation required.

In general, the system presents the necessity of local fuel processing. This is a chemical operation which the food processing industry may wish to avoid. The technology, although well developed, is probably not as proven as is that of the heterogeneous type operation.

It is estimated that the gaseous fission products represent about 15% of the total gamma decay available in fission products. This represents 0.15 x 5 or 0.75 Mev of gamma strength per fission.

Estimated power requirement for this design is:

$$P = 0.0167 \times \frac{195}{0.75} \times 1 \times \frac{1}{0.15} = 29 \text{ mw.}$$

theoretical power	production efficiency	volume efficiency (assuming no time delay between production and absorption on charcoal)	utilization efficiency
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Using Decay Gammas from Circulating Fuel of Homogeneous Reactor

This system will require local fuel processing and involves the technology of the homogeneous reactor. The gamma's decay activity of the circulating fuel may conveniently be piped to a point where it is to be used. However, this may be done only at a loss in volume efficiency and utilization efficiency (Delay neutron shielding) of the operation.

Estimated power requirement for this design is:

$$P = 0.0167 \times \frac{195}{5 \times 0.85} \times \frac{1}{0.25} \times \frac{1}{0.15} = 61 \text{ mw.}$$

theoretical power	production efficiency (gaseous fission products are not included)	volume efficiency	utilization efficiency
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Using Coolant Activated in Reactor Core or Blanket

This design involves the neutron activation of a nuclide circulating through the core or blanket of the reactor (either homogeneous or heterogeneous). This nuclide could be the core coolant, such as sodium. It could be dissolved as soluble salt in light or heavy water. Circulation would be through a closed loop including the reactor core, heat exchangers and the irradiation facility. The reactor type to be employed would be heterogeneous.

Chief advantages expected from such a system are:

- (1) It makes possible selection of an active nuclide whose decay energy and half-life are known.
- (2) The technology is well developed and a simple reliable system can be expected.

Chief problems involved in this system are:

- (1) The solution to be activated must be chemically and radiologically stable, and
- (2) The salt solution (if a solution is used) must surround the fuel elements -- "salting" may occur if any points of overheating exist. The alternative of retaining the solution in piping introduces metal as an additional poison in the reactor core.

The estimated power requirement for this system is:

$$P = 0.0167 \times \frac{195}{2} \times \frac{1}{0.25} \times \frac{1}{0.15} = 43 \text{ mw.}$$

theoretical	production	volume	utilization
power	efficiency	efficiency	efficiency

Final Choice of Reactor-Irradiation System

An inspection of the power required for each of the several reactor-irradiation systems discussed reveals no clear-cut distinction between most of the systems. Only the use of gamma radiation directly from the reactor core can be eliminated.

The heterogeneous reactor-activated coolant was chosen as the system to design. This decision was somewhat arbitrary. Other designs could probably be equally well developed. The heterogeneous design was chosen in order:

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(1) To follow the established technology and operational characteristics of the heterogeneous reactor, and

(2) To avoid the necessity for local fuel processing inherent in the homogeneous design.

The blanket of the homogeneous reactor could be utilized in much the same way as a solution blanket for a heterogeneous reactor with all of the advantages of a solution system.

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4.2 Seminar Report on Food Preservation

A seminar discussion on preservation of food by atomic radiation was held on October 21, 1955.

The discussion focused on the potential impact of a successful radiation preservation process on the food processing and distributing industries.

Technical papers considered by this seminar as the basis of discussion included: (1) Treatment of Foods by Ionizing Radiations by Office of The Quartermaster General, Department of the Army, (2) Impact of Peaceful Uses of Atomic Energy with Respect to Foods and Drugs, by Pure Food and Drug Administration, Department of Health, Education, and Welfare.

A summary of the discussion and the information contained in the background technical papers follows herewith.

Radiation preservation of foods should result in limited early benefits, but serious obstacles must be surmounted before use of this technique becomes widespread. There is no certainty that initial difficulties can be overcome, but only when the problems are solved will an industry develop and make its impact felt in related industries.

It can probably be assumed, however, that irradiated foods will be fit for human consumption. Experiments have not shown any harmful effects on animals fed irradiated foods. Experiments with humans, begun this year, have not shown any harmful results. Studies are being made under the direction of The Surgeon General to learn what toxicity hazards, if any, lie in radiation-preserved foods. To date all evidence has been negative. The studies will be completed in five years.

It should be emphasized that irradiated foods do not retain any residual radiation.

Food to be preserved by radiation may be given doses either of gamma rays or electron beams. There is no difference between the gamma rays and electron beams in their effect on bacteria and the changes in taste and

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smell which they bring about in foods. There is, however, a difference in the nature of treating the foods and the efficiency of the different methods used for sources of energy.

Gamma rays may be produced by radioactive elements or radioactive isotopes, or from man-made generators in the form of X-rays. Gamma-ray treatment has better penetrating characteristics, but efficiency is rated at only a 5% maximum in power reactors which are presently available. Use of radioactive materials as the source for gamma rays requires special licensing. Gamma-ray sources must be shielded when not in use.

Electron beams may also be utilized from radioisotopes, but the type of high intensity electron beams utilized in food preservation experiments may be best obtained from man-made particle accelerators.

Electron beam irradiation of foods for preservation requires tremendous sources of energy, utilizing millions of electron volts, although there is an inherent limit of about 20 million electron volts. At higher energies, residual radiation in the food may be produced. Treatment with energies of up to 6 million electron volts is effective to a depth of only 1 to 2 inches, enough for treatment of beefsteak, for example, but electrons of acceptable energies do not have the penetrating abilities to treat the depths involved in a side of beef. In addition, generators four to six times as powerful as those now available would be needed to approach production-line food-processing capacities.

The general advantages of electron irradiation are the efficiency of utilization — 60 to 75% of the available power can be utilized — the relative ease of operation and the need for few technical operating personnel.

4.2.1 Food Treatment

Most foods which are to be treated by radiation for preservation must first be packaged. The irradiation process destroys bacteria which cause food decay; unsealed foods would be subject to contamination subsequent to the irradiation process.

While the radiation-preservation process kills bacteria, it does not inactivate enzymes in living food tissues which change the flavor and odor

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of food. The current problem is how to kill the bacteria and still not bring about off-flavor, off-odor, or breakdown of the food tissues. Radiation in the frozen state or in the presence of an inhibitor, such as ascorbic acid, diminishes the production of off-flavor and off-odor. Radiation in the absence of oxygen also reduces off-odor.

Present experiments show there is near-term promise that a dozen perishables can be successfully treated by radiation so that they can be stored without refrigeration. These include asparagus, bacon, green beans, beef liver, broccoli, brussel sprouts, carrots, chicken, codfish cakes, pork, pork sausage, and waffles. Other types of food used in current experiments show lesser possibilities for successful irradiation processes. Irradiation of milk, butter, and cream, for example, has thus far resulted in preserved products with strong, objectionable odors.

Lesser dosages of radiation will serve to lengthen the refrigerated shelf life of a number of foods, with no major changes in flavor or odor. Relatively mild treatment will extend the shelf life of beefsteaks, hamburger, lamb, fish, luncheon meat, tomatoes, and other commodities by as much as 5 to 10 times.

A third phase of food irradiation, using even smaller dosages, appears to hold the most promise for early application. Assembly-line irradiation of grains should prevent infestation by insect pests which annually inflict heavy damage upon stored crops. Similar methods of radiation treatment have been successful in lengthening the storage life of potatoes and certain types of onions by delaying sprouting. Irradiation of potatoes also can control formation of sugars, a factor of importance to potato-chip manufacturers.

The lesser dosages of radiation also have been used successfully on pork to kill the trichina parasites, source of the human disease, trichinosis.

Following the five years which are required to finish present toxicity studies, it is estimated that another three to ten years may elapse before the food-processing industry would be able to apply these new techniques to meats, fruits, and vegetables.

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Commercial irradiation of foods will probably require an expanded governmental inspection program before such foods are placed on the market for home consumption. The Department of Agriculture has a large staff of food inspectors and a complete food-inspection program. Given properly trained personnel it could cover the irradiated food-inspection problem. The Pure Food and Drug Administration does not have the staff to make the necessary routine inspections at food-production plants; rather, it has concentrated on spot inspections to locate defective products. It would, therefore, have to set up a new organization to do routine food inspection.

Perhaps the greatest problem to be overcome before food irradiation has any impact is the problem of consumer acceptance. Even after it is established that irradiated foods conform to the present standards of safety, taste, odor, and color for public acceptance, a program of public education must follow, if public acceptance is to be achieved. Irradiated foods must, of course, be priced within a competitive range of other foods to gain acceptance.

Assumptions about the price of irradiated foods are most difficult, and cannot be made realistically at the present stage of development. No proven cost figures have been established, and no pilot-plant work is scheduled before 1958, so that accurate figures will not be available for some time. Preliminary estimates indicate that the costs of irradiating foods will probably range from 0.3 cents per pound to 7 to 10 cents per pound. The latest estimate places 7 cents as the highest limit and 4 cents as a probable value. This compares with 2 to 3.5 cents for frozen foods, 0.2 to 0.5 cents for canned vegetables, and 0.8 to 5 cents per pound for meat.

Should a commercially feasible method of food irradiation be developed and consumer resistance be overcome, food growers should generally benefit. Food irradiation would lengthen the period in which produce could be marketed, thus extending the market areas for fruit and vegetable farmers. The commercial acceptance of radiation preservation would also tend to encourage the development of fruits and vegetables particularly suitable for radiation treatment.

4.2.2 Food-Processing Industry

Preservation of foods by radiation seems unlikely to have any substantial impact for some years on the established food-processing industry. It is

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generally held that development of commercial food-irradiation processes will be gradual, and that the effects of such developments can readily be absorbed by most segments of the industry.

Radiation genetics appear to hold the most immediate promise of benefit to food processors. Uniformity in size, color, and flavor, higher yields, uniformity of set and position of the crop on the plant are of tremendous advantage in the mechanical harvesting and processing of agricultural products. Such factors are forecast through radiation genetics and should result in considerable savings to the growers, packers, and consumers.

4.2.3 Food Processing

Food processing is one of the Nation's greatest industries, representing an annual dollar volume of 58 billion. Of the total food product, an estimated 63% is processed in some form, and approximately 69% is packaged.

The Nation's food-processing plants are distributed strategically throughout the country, and commercial irradiation of foods should not require development of new plants or relocation of existing plants.

If the ultimate result of present research should be a method of food preservation which will supplant certain canned and frozen foods, then the long-range impact on the food-processing industry would be great. Of greater short-range importance, however, is the possibility that low doses of radiation will retard the rate of spoilage of fruits and vegetables which are to be canned or frozen, thus allowing processors additional valuable time in which to preserve their procedure by present methods. In such a way radiation would supplement, rather than supplant, present preservation methods.

Radiation preservation of fresh produce, or extension of the refrigerated life of perishables, would aid in solving present produce inventory problems which now include spoilage of up to 50% of some produce items between the farm and the consumer. Price variations in seasonal produce might possibly be minimized through the year, resulting in economies for growers, packers, and consumers.

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4.2.4 Food Packaging

Irradiation of foods could have substantial effects on the methods of packaging. Prepackaging of foods in production areas would overcome some present shipping difficulties and would bring about new efficiencies in both packaging and handling. The food-container industry would suffer only if severe competition were offered glass and tin containers by flexible packaging. Breakage and handling hazards of the flexible packages might indicate the continued desirability of the rigid containers. Costs of radiation preservation could be partially offset by the use of lighter steel for fabricating containers.

Prospects of longer shelf lives for foods should not alter materially the present picture for canned and frozen goods, inasmuch as spoilage is not a major factor. Present aseptic canning methods are aimed at a two-year storage maximum and each year the canning industry experiences a carry-over in large food packs, resulting in a drop in prices and a subsequent smaller pack the next year. Frozen foods may be expected to retain their flavor qualities for six days at 30°F, six weeks at 20° and six months at 10°. An area in which substantial economies might be realized through longer shelf lives is in the stockpiling of foods for military and civil-defense purposes.

4.2.5 Food Processing Machinery

No sudden shifts may be expected in the field of food-processing machinery. The food-processing industry is highly mechanized, and works on a continuous-flow assembly-line basis from field to preparation, packaging, and marketing. Irradiation of foods would require added capital outlays for equipment. Consumer acceptance, economies in the finished products, the seasonal use of such equipment, and other factors must be assured before the additional investments can be justified. The large manufacturers of food-processing equipment may be expected to take the lead in manufacturing irradiating equipment. By the same token, the larger food-processing firms may reasonably be expected to be the first to invest in radiation equipment.

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4.2.6 Food Merchandising

Food distributors will encourage growing new types of crops because they offer sales appeal to the consumer through introduction of new varieties in the diet. New varieties and new flavors are to the food industry what new models are to other industries.

The food distributors, however, may have a difficult problem in marketing radiation preserved foods. First will be the problem associated with all new products — encouraging the public to change its buying habits. The public's early experience with atomic energy was largely on the frightening side. As a result of confusion with radioactive fallout of atomic weapons, many persons fear all forms of radiation. Food distributors introducing radiation preserved food products must convince the public that the radiation treatment which the food receives is not harmful to those who eat it.

The food retailers, like the distributors, welcome the introduction of new varieties and new flavors. They tend to adopt new products quickly, provided they have public acceptance. A successful radiation preservation process would make it possible for retailers to offer consumers year-around garden-fresh fruits and vegetables for the first time. Reductions in food spoilage would not only bring reductions in distribution costs but also would result in increased availability of fresh fruits and vegetables.

4.2.7 Meatpacking

Precutting and prepackaging of meats at packinghouses would enable retailers to handle fresh meat with little or no further processing at stores and warehouses. If radiation preservation of meats is particularly successful, many meats and meat products could be handled in grocery stores without refrigeration. With refrigeration and freezer space costing over \$100 per square foot in the modern supermarket, as compared with \$20 per square foot for canned goods and staples, the potential savings could be significant. The consumer, in turn, would receive a fresh, carefully graded product. The labeling of meats would be as simple as the labeling of staples, and brand identification of an increased number of meat products for the consumer might tend to become widespread.

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The smaller, regional packinghouses, however, would have less need for radiation preservation where products are marketed rapidly. Cost and technical manpower factors also might make it uneconomic for smaller packinghouses to turn to radiation preservation.

4.2.8 Food Transportation

Successful irradiation of foods appears unlikely to bring about change in the food-transportation industry. While requirements for refrigerated transportation might be modified somewhat by use of radiation techniques, there will apparently still exist the need for protecting the irradiated foods against dehydration, freezing, and other excessive weather conditions which may be found between production centers and markets, and the existing insulated refrigerator car is best suited for this purpose. The demand should continue for rapid movement of foodstuffs to market to serve an ever-growing population with steadily increasing buying power, thus requiring a steady increase in food transport. Both pasteurization and food preservation by radiation would result in products packaged in such a manner as to require high quality of transportation equipment, either rail, truck, or plane.

4.2.9 Refrigeration

The refrigeration industry seems likely to suffer only minor setbacks as the result of a successful program of radiation preservation of foods. By far the largest segment — 80% — of the industry's gross annual sales is represented by home refrigerators. Since the main function of the home refrigerator is the storage of leftovers and refrigerated meal components, the use of radiation preservation would in no way affect this requirement. Once the package is broken on radiation-preserved food, it begins to decay in the same manner as fresh food.

The most immediate practical applications of food irradiation appear to be for deinfestation of grains prior to bulk storage — which would have no effect on the refrigeration industry — and low radiation dose pasteurization for meats, poultry, and fish, for the purpose of increasing the storage life of these foods while held in refrigeration. Such a development would reduce the demand for freezer equipment, but would seem to increase by a

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like amount the demand for cold-storage equipment. Even if radiation preservation techniques were to be perfected far ahead of the anticipated schedule, conversion from present food-processing methods to new methods would apparently be gradual. Thus any impact of radiation preservation on the refrigeration industry would be absorbed over a period of many years.

4.2.10 Summary

In summary, food irradiation appears to have its first large-scale application where low dosages are useful. Insect pests may be eradicated in stored grain; disease-bearing parasites may be destroyed; and the sprouting of tubers may be slowed. The refrigerated shelf life of certain meats, fruits, and vegetables may be extended. Major problems are yet to be surmounted in the effort to preserve foods by radiation, and the achievement of solutions cannot be forecasted accurately. Any general impact upon the food-processing industry may thus most likely be absorbed gradually over a period of years, in an evolutionary, rather than a revolutionary manner. As these technical developments do come about, however, their net effect on the individual consumer will be to increase the quantities and varieties of food available entirely apart from any actual services in the production of foodstuffs on the farms of the Nation. The result for the Nation as a whole will be a further accentuation of the national problems of food surpluses.

4.3 Treatment of Foods by Ionizing Radiations (A Survey of Current Status, September 10, 1955. Submitted by the Department of Defense)

The momentum behind the concerted effort to develop the process of irradiation of food stems from a multiplicity of beneficial avenues.

First, there are the potential contributions toward lessening the incidence of diseases throughout the world. A significant number of the American people are affected by trichinosis. Treatment of food by ionizing radiation has been shown to kill the helminthic parasite without changing the appearance or flavor of fresh pork causing trichinosis. It is believed that comparable results are in the offing for helminthic diseases in general, as well as food-borne bacterial diseases, such as Salmonellosis.

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Second, there are the potential contributions toward alleviation of the worldwide Malthusian food dilemma. The present world population of 2 1/2 billion is growing at the rate of nearly 100,000 a day. The challenge of meeting the higher food demands at ever-rising standards must be met. The various instruments toward this never ending goal include the increasing of yields from farms now under cultivation, the bringing of new lands into utilization, the improving of methods of distribution to dissolve the specter of localized oases of farm surpluses in an enveloping desert of scarcity and the reducing of heavy losses during storage and shipment between the farm and the dinner table. It is in the latter two categories that food processing with ionizing radiations promises significant returns.

The capabilities of the treatment in reducing the requirement for refrigerated handling of perishables can extend their distribution to peoples in lands not blessed with modern storage facilities. The stretch-out of the storage life of tubers can help the farmer in his marketing activities. The ready destruction of insects infesting grain can assist materially in combating the large losses, estimated at varying figures up to 50% for the hot and humid areas of the world. The killing of insect larvae can free some fruits from the present shipping restrictions imposed by interstate and international commerce practices as a quarantine against the spread of plant diseases.

Third, there are the potential contributions toward materially assisting the emergency nuclear energy industry in solving its problems of waste disposal and economics. Rapid progress must be made in developing nuclear power to assist in meeting the projected threefold increase in world energy demand by the year 2000. If the present uranium and thorium systems are used in the nuclear production of electrical power, it is envisioned that large amounts of radiation and radioactive fission products will be produced. The fission product to be available in the world has been approximated at 400 tons annually for the foreseeable future. The more efficient disposal schemes require separation of the longer-life isotopes of cesium and strontium from the less persistent ones. The latter can then be disposed after a reasonable length of storage. The inevitable question arises

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as to the fate of the cesium and strontium, which require about 600 years of natural decay before their radioactivity dwindles to concentrations in their original liquid wastes to levels considered safe for human drinking.

The use of these long-life fission products in the irradiation of food represents a promising outlet. The possibilities of ancillary income from optimization of reactor design for radiation availability; from sale of fission products and from rental fees associated with the use of fuel assemblies during their period of cooling constitute possible means of narrowing the price gap between nuclear and conventional electricity.

Fourth, there are the potential contributions toward increasing the standard of living of our own people at home. For the last century there has been a distinct increase in the simplification of food preparation so as to ease the work of the housewife. The improvement of canned goods following their invention during the Napoleonic war has resulted in a wide array of prepared foods ready for immediate consumption. The most recent innovations in simplified dinner preparation are frozen precooked meals and ready-to-bake goods, such as cinnamon rolls and waffles.

Irradiation by ionizing radiations show distinct possibilities in joining with these advances to increase their ultimate benefit to the American public. It is envisioned that the taste of some canned products may be significantly improved through replacement of heat by cold irradiation as a method of sterilization. There are also possibilities of superior retention of nutrients. In the area of ready-to-bake goods, irradiation may drastically reduce or eliminate the necessity for refrigerated handling, thereby greatly facilitating their distribution.

Fifth, there are the potential contributions to improving the efficiency of our Armed Forces. As a leading world power, the United States will probably be required to deploy her troops on a global basis during periods of emergency. The logistic support of these farflung forces will tax our national resources. New methods must be found to decrease the burden. The same telling advantages described in the previous civilian examples will accrue to the members of our Armed Forces by the successful development of the irradiation of food. The impact of the resulting improvement

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in the nutritional level of our troops and the easing of the military subsistence supply system, involving an annual food bill of nearly a billion dollars, will add considerably to their combat effectiveness in the defense of our Nation.

Viewed within the context of these five incentives, it is readily conceivable why research on the irradiation of food is receiving its present impetus.

4.3.1 Present State of the Art

1. General statement

There are four primary considerations which must be faced in developing the process of irradiation of food by ionizing radiations. They are:

First, there must be no reasonable doubt but that ionizing radiations are capable of destroying micro-organisms, insects, and helminthic parasites infesting foods.

Second, there must be no reasonable doubt but that irradiated foods are wholesome for continued human consumption and not radioactive.

Third, the irradiated foods, though nontoxic and nutritious, must, at the same time, be acceptable in flavor, odor, and appearance to the consumer.

Fourth, the process needs to be technologically practical and economically attractive.

The subsequent paragraphs of this section will delineate the state of the art in the various aspects of these four primary areas.

2. Destruction of micro-organisms, insects, and helminthic parasites

Experiments have conclusively demonstrated that all living organisms can be killed by ionizing radiations, provided a sufficiently high dose is administered.

In general, the lower in the evolutionary scale the higher is the dosage required. The simpler and the smaller the organism the less sensitive it is to radiation damage. Thus, while insects can resist only a twentieth of the lethal dosage for micro-organisms, man can only stand a thousandth.

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Among micro-organisms themselves there is considerable variation in radiosensitivity. Similar differences in susceptibility between species are noted among insects. The response is also affected by the composition and acidity of the nutrient medium, the presence of oxygen, and other environmental conditions. Taking all of the variations into account, the following dosages represent fair approximations:

- (a) For sterilization of food involving complete destruction of all living organisms: 2 million rep.
- (b) For pasteurization of foods, involving partial destruction of micro-organisms: 200,000 rep.
- (c) For destruction of insects in foods: 30,000 rep.
- (d) For destruction of helminthic parasites: 30,000 rep.
- (e) For inhibition of sprouting of tubers: 12,000 rep.

The delivery of these dosages is well within the capabilities of contemplated beta and gamma sources. The first step of assured destruction of living organisms has been well laid.

3. Wholesomeness of irradiated foods

An extensive program is being sponsored by the Department of the Army with the guidance of the Food and Drug Administration. So far, all results on wholesomeness have been encouraging.

Neutrons, and electrons above 20 Mev., which may produce secondary activity, are not contemplated for the irradiation of food. With the gamma and beta rays currently being investigated, there is no induced radioactivity. Measurements on irradiated foods by means of the most sensitive detectors cannot reveal any induced radioactivity. Neither did the cobalt-60 radiation of 24 elements found in food cause any secondary radioactivity.

Two preliminary 3-week human feeding tests have been completed, in which volunteers were fed 35% of their diet as irradiated food. There has been absolutely no difference noted between the individuals fed irradiated meals and those fed the unirradiated. Experiments of this kind are being expanded, wherein both the percentage of irradiated food in the diet and the duration of the test runs will be gradually increased.

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As far as the wholesomeness of irradiated foods is concerned, all experiments to date indicate their fitness for human consumption. Because of the potential widespread use of irradiated foods, however, we are being conservative in our approach and are massing an overwhelmingly convincing array of information before proclaiming a final verdict.

4. Consumer acceptability of irradiated foods

Foods do not react alike to a given dose of radiation. There are maximum levels of radiation that can be tolerated by various foods without becoming unacceptable in either flavor, odor, or appearance. The values range from below 100,000 reps. for milk to above 3 million for prunes. Much of the data from different laboratories appear contradictory, due to varying techniques and conditions of irradiation. It is known, for example, that the generation of irradiation odors and flavors is influenced by the presence of oxygen, antioxidants, free-radical acceptors, and temperature. Removal of oxygen, addition of ascorbic acid, and freezing decrease the undesirable changes in some instances.

5. Sources of radiation

The different sources of beta and gamma rays potentially available to the food processor are fairly clear at this point. What is uncertain are their respective speed of development, convenience in use, and cost. An analysis of these questions is being undertaken and should be completed within a year.

Pending the outcome of this study we may speculate on the subject. As a point of departure the food processor may align himself with the growing nuclear energy industry as a user of its radiation sources and fission products. Being in the nature of a surplus commodity, at present, their cost may prove sufficiently low to be attractive. The following avenues are open to him:

(a) Spent fuel assemblies — During the cooling period between discharge from the reactor and processing in the chemical plant, the strong radioactivity of fuel assemblies can be exploited. Assemblies providing as high as 4×10^7 r per hour are being used in current tests. It has been estimated that a sizable nuclear power station can keep several food-processing plants supplied with radiation from cooling fuel elements.

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(b) Cesium¹³⁷ — This gamma-emitting isotope will in all probability be separated with strontium⁹⁰ from the rest of the shorter life waste fission products for easier waste disposal. A pilot plant will be completed within two years by the Atomic Energy Commission at Oak Ridge to effect such a separation. About 200,000 curies of cesium¹³⁷ is estimated to be the annual production.

If this isotope with a half life of 33 years emitting a 0.662 million electron volts gamma and 0.518 and 1.18 million electron volts betas is available in megacurie quantities, consideration can be given to its use in food processing. Unfortunately, it is not expected that such an amount can be realized for at least several years to come. This dampens expectations of its early use. Furthermore, the American price for cesium¹³⁷ has not been set, although British estimates run about \$4.50 per curie. If the latter value holds, megacurie sources of cesium needed for production may prove too expensive as a source of gamma rays for food processing.

(c) Strontium⁹⁰ — Strontium⁹⁰ with its 28-year half-life, emitting 2.24 and 0.54 million electron volts betas, can be used as a source of beta rays for the irradiation of food. Unfortunately its future is shrouded in the same haziness as has just been described for cesium¹³⁷.

(d) Gaseous fission products from homogeneous reactor — The fission gases from a homogeneous reactor as presently designed are bled onto a charcoal bed. It is conceivable that the gamma emitting gases can be drawn from the reactor via a loop into an irradiating chamber outside of the reactor. It has been estimated that from a 5-megawatt reactor 3 megacuries of gamma activity can be obtained, especially if the short-lived xenon and krypton can be captured.

The principal disadvantage to such an arrangement is too direct a coupling of food processing times with power production. There may be periods when only 1 of the 2 activities may be demanded. Such occasions would strain the otherwise mutually advantageous relationship. Another troublesome feature, common also to the 2 succeeding examples, is the requirement that food must be processed at the reactor site.

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Discussions have been held concerning experiments to test the concepts using the homogeneous reactor test being completed at Oak Ridge.

(e) Circulating fuel from a homogeneous reactor — Pumping the radioactive homogeneous fuel from the core to an external irradiating facility is another possible way of coupling gamma irradiation with power production.

In view of the fact that such a loop has neither been constructed nor designed, more detailed discussion would be unwarranted. It may be well to point out, moreover, that besides gamma and beta radiations, neutrons will also be emitted. Precautions must be taken to shield these neutrons from bombarding the food and possibly inducing secondary radioactivity.

(f) Chemical extraction of fission products from circulating fuel solution — According to preliminary estimates this source should yield radiations 20 times as intense as the gaseous fission loop described previously. However, the method has not yet been developed, although much thought is being devoted to it.

(g) Reactor-produced isotopes — The most well-known is cobalt-60, emitting 1.33 and 1.17 million electron volts gammas with a half-life of 5.2 years. This has been used extensively in experiments on the irradiation of food. It proved extremely simple in actual operation and has many desirable features. Aside from cost and availability it would be an attractive source.

The largest source of cobalt-60 which has been used for food irradiation is 10 kilocuries. For a production line, megacurie quantities are required. This is contrasted to the estimated annual production of United States and Canada of 120,000 curies. It would be possible to boost this amount immeasurably through the use of the production reactors at Savannah and Hanford. However, these latter units, at least up to now, have been reserved for higher priority duties.

The cost of \$5 per curie also decreases somewhat the attractiveness of this isotope as far as food irradiation is concerned.

The coupling of food irradiation with the nuclear electrical power industry poses the fundamental problem of how much influence the source

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of a subsidiary income can exert on the major activity in looking after its own interest. What would happen if the demand for power happens to decline, when that for food irradiation has not? What would happen if an alternate use develops a decade later for the irradiation facilities which may be able to pay a higher order of price? Can the low-cost food-processing industry meet such competition? What would happen to the capital investment in the food-processing plant geared to the present uranium and thorium type of nuclear power stations, if decades later the latter is rendered obsolete by, say, controlled fusion reaction?

Faced with these basic uncertainties, the food processor may wish to set himself up in business independent of the power industry as far as irradiation services go. If this is his preference, the following alternatives are open:

(a) Reactor — Nuclear reactors may be designed for the express purpose of generating beta and/or gamma radiations, with power as purely subsidiary. The latter may be in the form of low-grade steam, space heating, and miscellaneous electrical uses.

General designs have been considered by reactor engineers. North American Aviation, Inc., has described the potentialities and characteristics of a homogeneous reactor using enriched uranium sulfate in water in a core 18 inches in diameter, operating at 135°C and 60 psi. Fission gases and an activated manganese sulfate reflector solution are used as gamma irradiating sources. An 11-megawatt reactor of this type was estimated to be capable of sterilizing 2 tons of meat per hour.

The Oak Ridge School of Reactor Technology has completed a design study of a heterogeneous reactor for the purpose of providing gamma radiation instead of power. In this model, aluminum clad MTR rods are to be used. A circulating loop of an aqueous solution of indium sulfate extends into the reactor and out to a radiating facility for food processing. The indium is rendered gamma-emitting by bombardment with neutrons within the reactor core. A 17-megawatt reactor is considered capable of sterilizing 4 tons of meat per hour.

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Unfortunately, these studies are only paper ones and no plans are underfoot to seriously test the concepts experimentally. The gamma-producing reactor is not part of the Atomic Energy Commission's reactor development program and it is unlikely that private industry will pursue the problem vigorously for at least another 5 years.

(b) Electron generators — The use of electrons is limited fundamentally by the depth of penetration at a given energy level and the possibility of induced radioactivity at energies above 20 million electron volts. For each million electron volts, about an eighth of an inch of meat can be penetrated with fair uniformity of dose. If the meat is irradiated from both sides with the same beam, the effective thickness can be increased $2 \frac{1}{2}$ times. Thus, a double pass of 1 million electron volt electrons is capable of effectively sterilizing a steak five-sixteenths inch thick. If for the moment we consider 15 million electron volts as the safe energy limit from the standpoint of possible induced radioactivity, then the food processor should be able to sterilize steaks $1 \frac{7}{8}$ inches thick in a single pass of electrons or a cut of meat over $4 \frac{1}{2}$ inches thick with irradiation from both sides.

There are two obvious advantages in employment of electron generators which appeal to food processors. One is their safety in operation. The other is the freedom from governmental practices and policies regarding the use and supply of reactor fuel and isotopes.

At the present time it is difficult to select the most suitable of the different sources of radiation. We will have a better footing after completion of the study referred to at the beginning of this section. Even then we will have to extrapolate over many gaps and hazy spots in our knowledge. This is especially true as far as radiation sources dependent upon nuclear reactors are concerned. We feel more certain of our figures in the case of electron accelerators. Tentatively, then, we may say that for foods of thicknesses below 3 inches, the electron accelerators appear attractive. Production size sources can be manufactured within two years. For much greater thicknesses, of course, we must turn to gamma rays. Unfortunately the economics and convenience of the gamma sources derived from reactors

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are vague at the moment. If the present rate and nature of the reactor development programs in this country are continued, it would not appear that production quantities of fission waste isotopes, Cobalt-60 or gamma-producing reactors will become available to the food industry within the next decade.

6. Food processing lines

It is not envisioned that the irradiation of food will drastically alter the food packaging and preparation lines, in which substantial capital has been invested. In most instances the irradiation treatment will be carried on subsequent to the packaging operation. There may be departures from this usual practice, such as the sterilizing of thin layers of food by means of ionizing radiations followed by aseptic packaging. Depending upon the specific product, the sequence of the processing steps will vary. Several representative schemes are briefly presented below.

(a) Sterilization — The irradiation source can be located immediately following the can sealing machinery and the exterior live steam can washer. This involves a substitution of the retort in the normal thermal processing line by the gamma or beta generators, if sterilized uncooked fresh foods are desired.

If canned cooked foods with improved flavor are being manufactured, the sterilizing irradiation source may be placed either before or after the retorting step, depending upon the results of pending investigations. In this case the retort will likely still be required to give the canned goods a moderate heat treatment for optimal cooking purposes, which destroys much of the taste and texture of thermally processed foods. The retort will not be necessary if studies underway show that foods can be simultaneously heated and irradiated without adverse effects and that the heat as well as the ionizing radiations from gamma sources can be controlled in actual use.

With aseptic canning systems, the irradiation can take place immediately before the sterile filler and canning operations.

(b) Pasteurization — In the case of vegetables, irradiation can be carried out at the end of the processing line, following washing, cutting, grading, blanching, draining, and packaging.

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(c) Insect destruction — For deinfestation of grains before storage in bulk form in grain elevators, the optimal location for the irradiation facility would be between the bucket elevators and the principal storage bin. Irradiation would follow the scalper, which removes foreign matter and the hopper scale, from which the grain is carried by bucket elevators to the bins.

(d) Destruction of trichina in pork — The gamma source can be located immediately after the slaughtering and dehairing operations. The entire hog can be passed by a monorail system through the gamma field.

Such a step is unnecessary if the pork is to be subsequently sterilized or pasteurized. Dosages employed in these instances will destroy the trichina as well as the micro-organisms.

(e) Inhibition of sprouting of potato — With gamma sources, potatoes may be sacked either before or after irradiation, depending upon local preference.

The above examples suggest that the advent of irradiation will not significantly disrupt the food processing line. It should be noted, however, that although many sketches and diagrams have been presented in various publications, no food processing pilot plant in which irradiation is an integral step has yet been built or designed. The Department of Army plans to have such a facility ready to process 1,000 tons per month by 1958. Only after experience with its operation can the economics and feasibility be ascertained with reasonable assurance.

7. Packaging and storage

No exceptional storage problems are anticipated. Conventional methods of handling, storage, and shipment appear entirely satisfactory.

As far as packaging is concerned, the same general situation holds, although some consideration must be given to the best material for the different treatments.

For the sterilization of fresh meats and vegetables, films which are impermeable to water and oxygen, resistant to 3 million reps of beta and gamma rays, and of sufficient durability are desired. There are commercial

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films available today which meet the minimum requirement. There is no reason to doubt that given the demand their properties will be immeasurably improved.

For the radiation sterilization of canned cooked foods as a means of improving their flavor and texture, resistance of the package to heat must also be considered. It is probable that for this purpose the present cans may remain in use. The fact that they absorb a significantly greater fraction of the radiant energy than do cans of aluminum or plastic films may require further examination before a definitive statement can be made.

For the deinfestation of packaged grains for long-term storage, a material must be used which is impervious to insect penetration and reinfestation. Rapid progress is being made in this direction and this too, does not appear too great an obstacle.

8 Economics

There are no proven figures on the cost of irradiating foods. This is principally due to the fact that pilot-plant quantities of foods have not heretofore been studied and daring assumptions had to be made in the many estimates advanced to date. A pilot plant processing 1,000 tons of food per month is being scheduled for 1958 by the Department of the Army. A thorough economic analysis is being carried out by North American Aviation, Inc., under contract to the Department of the Army, to be completed within the next year.

In the meantime many calculations have been made on irradiation processing costs. In general those based on the use of isotopes and fission products have been additionally handicapped by the lack of firm prices for the source material itself. The electron generators are not confronted with this problem to as marked an extent. Tables 4.6, 7, and 8 present typical cost estimates for irradiating foods by linear accelerators, reactors built solely for gamma irradiation and fission products, respectively. The essence of these and other estimates in the literature can be summarized as follows:

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Sterilization of meat (2 million rep) by —

Cathode ray generators: 1 to 5 cents per pound.

Linear accelerators: 0.3 to 2.5 cents per pound.

Megacurie cesium — 137 at \$5 per curie: 3 to 10 cents per pound.

Soft X-ray machines: 4 to 5 cents per pound.

Reactor, homogeneous (no credit for power, only fission gases used): 7 cents per pound.

Reactor, heterogeneous (no credit for power, only gamma from indium loop used): 1.2 to 4 cents per pound.

Deinfestation of grains (30,000 rep) by —

Linear accelerators: 10 to 74 cents per ton.

Reactor, homogeneous (no credit for power, only fission gases used): \$1 per ton.

Inhibiting sprouting of potatoes (10,000 rep) by —

Linear accelerators: \$0.14 to \$1 per ton.

Fission products: \$3.50 to \$5 per ton.

Reactor, homogeneous (no credit for power, only fission gases used): \$1.30 per ton.

It would not be amiss to reiterate the highly assumed basis for most of the figures given above. Caution must accompany their use. They are quite indicative of the orders of magnitude of costs, however, pending the time when more accurate economic analyses and pilot-plant runs on actual foods have been completed.

In view of the wide range of estimates as to the cost of irradiation at the present time, it seems unwarranted to compare the total cost per pound for preservation, storage, and transportation of perishables preserved by irradiation with that by other means. For general reference purposes, however, the costs of conventional processing and handling are listed below.

(a) Freezing: 0.2 to 0.4 cents per pound.

(b) Cost of producing frozen foods: 2 to 3.5 cents per pound.

(c) Heat processing of canned goods: 0.15 to 0.5 cents per pound for vegetables and 0.8 to 5 cents per pound for meats.

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Refrigerated storage for fresh meats range approximately between 20 to 60 cents per 100 pounds per month as compared to 3 to 6 cents for unrefrigerated storage of canned processed foods.

Approximate shipping costs between refrigerated and nonrefrigerated foods are:

(a) San Francisco to Japan: Refrigerated, 6.4 cents per pound; nonrefrigerated, 1.9 cents per pound.

(b) New York to Germany: Refrigerated, 2.1 cents per pound; nonrefrigerated, 1.5 cents per pound.

(c) Chicago to San Francisco: Refrigerated, 2.1 cents per pound; nonrefrigerated, 1.5 cents per pound.

(d) Chicago to New York: Refrigerated, 0.9 cents per pound; nonrefrigerated, 0.85 cent per pound.

From the standpoint of processing costs, it appears that the treatment of foods by ionizing radiations lies in the same order of magnitude as conventional techniques. Cost of handling subsequent to treatment appears to be lower. We should bear in mind, however, that cost alone should not be considered the principal advantage of the irradiation of food by ionizing rays. It lies primarily in the new benefits to be derived.

4.3.2 Major Unresolved Questions

As in the case of any new field of research the number of scientific and technological questions are innumerable. The optimal type of rays for individual foods and purposes, the methods of measuring the dosage of radiation received in foods, the geometrical arrangement of irradiation sources, the techniques of microbiological control, the inactivation of enzymes, the relationship between irradiation dose and subsequent or prior heat treatment, the place of blanching and high frequency as cotreatment with irradiation, the storage characteristics of irradiated foods, the selection of most suitable packaging methods, the food-conveying and food-handling facilities, shielding requirements around the radiation source, the radiological safety monitoring and practices, the economic analyses of various systems — these are some examples. At the present moment, none of them appear so formidable an impediment as to deny the eventual success of the processing of food by

ionizing radiations. However, there are several areas which require concerted attack. A brief description would be in order.

From the psychological as well as the scientific standpoint, the question of the wholesomeness of irradiated foods must be pursued with increased vigor. Interviews with representatives from all over the world showed that the first question that comes to their minds when irradiated food is mentioned is: Is it toxic? Undoubtedly, their unfamiliarity with the process coupled with their fears of vague things connected with atomic bombs and energy make them unduly suspicious. Nevertheless, their conservative attitude must be appreciated if we hope some day to be able to offer irradiated foods to the public. This consideration is quite apart from the fundamental wisdom of being convinced ourselves beyond any reasonable doubt that irradiated foods are entirely wholesome.

The uncertainty surrounding the cost and dependable availability of fission products from the reactor programs hampers the reliable evaluation of the commercial feasibility of food-processing plants based on their use. Lack of experience in reactors designed primarily for gamma radiation leaves the second source of gamma radiation unsettled. Unless much more data are forthcoming from these areas in the next two years, which are beyond the control of Department of the Army's food-irradiation project, it may well be that we will be forced to devote our main attention to electron generators. Knowledge as to what the latter can do is far more definite. To do this, however, would mean forsaking attempts to irradiate materials exceeding 5 inches in thickness, such as sacks of grain or sides of beef. This is not a desirable turn of events, especially during the exploratory stage. It appears that a bolder attack upon clarifying the uncertainties surrounding large gamma irradiating sources is called for.

A more diffused problem is that of taste, odor, and appearance brought about by irradiation. As has been discussed in the earlier sections, the response varies from food to food — from the stable pork to the sensitive milk. It is expected that preventive treatments may not be universally applicable, although freezing and deoxygenation have been found generally helpful. Only a constant bearing down upon each individual food will

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uncover the secret for that particular commodity. This implies long and painstaking studies on individual food items.

4.3.3 Outlook

The potential benefits to our country and to peoples all over the world from the successful development of the treatment of foods by ionizing radiations are great indeed. So are the technical questions to be solved before its realization. Through the stout support of the President and the Congress, scientists in this country have been able to direct substantial effort toward the resolution of the various questions. So far, they have been highly successful. Within the brief span of the last three years, the prevailing outlook in this country changed from one of cautious skepticism to optimism. Food processors are predicting that commercialization of the process will be realized anywhere between 5 and 20 years from now. Although there still remain many difficult problems yet to be faced, each passing day brings increasing confidence in early success.

Table 4.6

Estimates of radiation processing costs using
electrons from linear accelerators¹

Application	Dosage required (rep)	Available model, 6 Mev. 4 kw.		Proposed model, 25 Mev. 60 kw.	
		Pounds per hour	Cost per pound	Tons per hour	Cost per ton
Pasteurizing meat	100,000	16,500	1.2 mil	125	\$0.34
Trichinosis control	25,000	66,000	0.3 mil	500	.09
Sterilizing foods	2,000,000	850	2.4 cents	6.4	6.40
Sprout inhibition of potatoes and onions	10,000	40,000	\$1 per ton	300	.14
Deinfestation of grains	15,000	110,000	37 cents per ton	800	.05

¹Figures provided by Applied Radiation Corp. If X-rays are used processing rates are to be reduced (except potatoes) 4-fold and costs increased 4-fold.

Table 4.7

Estimates of radiation costs for a homogeneous reactor utilizing only radiations from fission gases without credit for possible heat or power production¹

Product and process	Production rate, pounds per hour	Radiation required (rep)	Nuclear-reactor size (mega-watts)	Approximate reactor cost	Approximate processing cost (cents per pound) ²
Snap beans (sterilization)	6,000	1,500,000	12.2	\$4,000,000	5.5
Grain (insect control)	1,500,000	30,000	61	10,000,000	.05
Canned meat (sterilization)	5,400	1,500,000	11	4,000,000	5.5
Fresh beef (pasteurization)	27,000	80,000	2.9	1,800,000	.5
Potatoes (sprouting control)	100,000	20,000	2.7	1,700,000	.13

¹Figures provided by North American Aviation, Inc.

²Assuming a 20% efficiency of gamma ray absorption by the product and assuming a 300-day, 20-hour per day operating schedule.

Table 4.8

Estimates of radiation processing costs for inhibiting the sprouting of potatoes using waste fission products¹

Source of radiation	Production in bushels per year	Cost per ton
Cesium-137	1,120,000	\$3.91
Mixed fission products (2-year old)	1,120,000	4.98
Fuel assemblies	1,060,000	3.62

¹Figures obtained from University of Michigan, Engineering Research Institute, Progress Report No. 7, December 1954.

Production and cost based on dose of 10,000 rep, operating for 16 hours per day and 260 days per year.

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(The following, although not used specifically in this study
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