UNITED STATES ATOMIC ENERGY COMMISSION

A FOOD STERILIZATION REACTOR

Reactor Design and Feasibility Problem

By

E. O. Guernsey

R. M. Ball

T. V. Kavanagh

C. T. McDaniel

G. T. Schnurer

C. E. Whittle

August 1955

Oak Ridge School of Reactor Technology
Oak Ridge, Tennessee

Technical Information Service Extension, Oak Ridge, Tenn.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

This report has been reproduced directly from the best available copy.

Since nontechnical and nonessential prefatory material has been deleted, the first page of the report is page 5.

Printed in USA. Price \$3.00. Available from the Office of Technical Services, Department of Commerce, Washington 25, D. C.

PAGES 3 to 4

WERE INTENTIONALLY
LEFT BLANK

CF-55-8-190(Rev.)

OAK RIDGE SCHOOL OF REACTOR TECHNOLOGY

Reactor Design and Feasibility Problem

"A FOOD STERILIZATION REACTOR"

E. O. Guernsey, Group Chairman

R. M. Ball

T. V. Kavanagh

C. T. McDaniel

G. T. Schnurer

C. E. Whittle

OAK RIDGE NATIONAL LABORATORY

Operated by

Union Carbide Nuclear Company

Oak Ridge, Tennessee

August, 1955

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

PREFACE

In September, 1954, a group of men experienced in various scientific and engineering fields embarked on the twelve months of study which culminated in this report. For nine of those months, formal classroom and student laboratory work occupied their time. At the end of that period, these six students were presented with a problem in reactor design. They studied it for ten weeks, the final period of the school term.

This is a summary report of their effort. It must be realized that, in so short a time, a study of this scope can not be guaranteed complete or free of error. This "thesis" is not offered as a polished engineering report, but rather as a record of the work done by the group under the leadership of the group leader. It is issued for use by those persons competent to assess the uncertainties inherent in the results obtained in terms of the preciseness of the technical data and analytical methods employed in the study. In the opinion of the students and faculty of ORSORT, the problem has served the pedagogical purpose for which it was intended.

The faculty joins the authors in an expression of appreciation for the generous assistance which various members of the Oak Ridge National Laboratory gave. In particular, the guidance of the group consultants, R. N. Lyon, R. W. Peelle, and H. R. Zeitlin, is gratefully acknowledged.

Lewis Nelson

for

The Faculty of ORSORT

ACKNOWLEDGEMENTS

We would like first to express our thanks to R. N. Lyon (ORNL) who has served as principal advisor to the group. Other advisors who have given much help were R. W. Peele (ORNL) and H. R. Zeitlin (ORNL).

Reactor calculations were made with assistance from R. R. Bate, T. B. Fowler and A. M. Perry, all of Oak Ridge National Laboratory.

J. A. Ghormley (ORNL) and C. J. Hochanadel (ORNL) have helped with advice concerning questions of chemical and radiological stability.

We would like to thank other ORNL personnel for help in particular phases of the study. They are:

I. Spiewak and R. Van Winkle during preliminary discussions about the possible use of a homogeneous reactor.

H. P. Yockey during discussions and calculations of permissible thermal neutron exposure during processing of beef.

M. I. Lundin during preparation of the cost analysis.

Representatives of both the Quartermaster Corps and the Army Reactors Branch of the AEC have shown an active interest in the project. Thanks are due, in particular, to Lt. Colonel Belmont S. Evans, Jr., who has acted as liaison officer between this group and the Quartermaster Corps.

ABSTRACT

A study ^{was} ~~has been~~ made to determine the feasibility of sterilizing beef with reactor-produced gamma radiation.

Results of the study ^{were} ~~have been~~ measured against specifications established by the U. S. Army Quartermaster Corps and against estimated results for meat sterilization with other sources of radiation. A conceptual design for a reactor-irradiation system, involving activation of a medium in the blanket of a heterogeneous reactor, satisfies these specifications. It compares favorably with other sources of radiation. (auth)

Further work to improve the reactor - irradiation system is recommended.

TABLE OF CONTENTS

1.0	Introduction	
1.1	Background of the Study	15
1.2	Bases and Objectives of the Study	16
1.3	Scope of the Study	17
2.0	Conclusions and Recommendations	
2.1	Feasibility of Meat Processing with Reactor Produced Gamma Radiation	19
2.2	Processing with Coolant Activated in Core or Blanket of Heterogeneous Reactor	19
2.3	Recommendations for Future Work	21
3.0	General Considerations	
3.1	Technology of Food Processing by Irradiation	22
3.2	Public Acceptance of Irradiated Food	24
3.3	Industrial Acceptance of Radiation Processing	25
3.4	Other Sources of Sterilizing Radiation	25
3.4.1	Cost	26
3.4.2	Uniformity of Dosage	26
3.4.3	Versatility	26
3.4.4	Time Dose Comparison	28
3.5	Preliminary Calculations	28
3.5.1	The Processing Rate	28
3.5.2	The Theoretical Power Requirement (Energy Deposited in Meat)	29
3.5.3	The Processing Volume	29

4.0	Choice of Reactor - Irradiation System	
4.1	Introductory Remarks	30
4.1.1	Criteria for Choice	30
4.1.2	Limits of Neutron Exposure	31
4.2	Use of Direct Fission Gammas and Decay Gammas Directly from a Heterogeneous Reactor Core	32
4.3	A Heterogeneous Reactor Operated Intermittently	34
4.4	Use of Gaseous Fission Products from a Homogeneous Reactor	35
4.5	Using Decay Gammas from Circulating Fuel of Homogeneous Reactor	35
4.6	Using Coolant Activated in Reactor Core or Blanket	36
4.7	Final Choice of Reactor - Irradiation System	37
5.0	Selection of the Coolant to be Activated in the Reactor	38
6.0	Design of Reactor Core	
6.1	Reactor Type	43
6.2	Nuclear Constants	46
6.2.1	Resonance Escape Probability for Indium Sulfate Solution	46
6.2.2	Other Constants	47
6.3	Criticality Calculations	48
6.4	ORACLE Vs Hand Calculations	58
6.5	Fission Product Poisons	59
6.6	Fuel Burn-out	61
6.7	Activator Burn-up	63
6.8	Temperature Coefficients	64
6.9	Control Rods	65

6.10	Equilibrium Time and Residual Activity in Coolant	66
6.11	Optimizing Blanket Volume	68
7.0	The Irradiation Facility	
7.1	Introduction	73
7.2	Geometry of the Source	73
7.3	Effect of Specific Activity of Source and Processing Time on Volume of Irradiation Source	74
7.4	Mechanical Design of Source Volume and Food Carrier	82
7.5	Shielding and Refrigeration of Irradiation Facility	86
7.6	Economics of the Irradiation System	87
7.6.1	Concrete Shielding and Housing	87
7.6.2	Conveyor Cost	87
7.6.3	Source Slab	87
7.6.4	Refrigeration Costs	90
8.0	Design of Combined Reactor - Irradiation Systems	
8.1	Introductory Remarks	91
8.2	Bases of Calculations	92
8.3	Method of Calculation	93
8.3.1	Flux at Center of Reactor	93
8.3.2	Reactor Power	94
8.3.3	Flux Ratio	94
8.3.4	Neutron Captures in Indium	94
8.3.5	Blanket Volume	94
8.3.6	Heat Removal	94
8.3.7	Flow Rate	94

8.3.8	Pipe Volume	94
8.3.9	Flash Cooler Volume	95
8.3.10	Total Volume Exclusive of Irradiation Volume	95
8.3.11	Source Volume Vs. Source Strength	95
8.3.12	Graphical Solution	95
8.3.13	Efficiencies	96
8.4	Workable Reactor - Irradiation Systems	98
8.4.1	Activation of Manganese in Blanket	98
8.4.2	Activation of Manganese in Reactor Core	98
8.4.3	Activation of Indium in Reactor Blanket	98
9.0	The Cost Estimate	
9.1	Purpose	106
9.2	Scope	106
9.3	Systems	106
9.3.1	Power Generation Cases	106
9.3.2	No-power Cases	107
9.4	Bases of the Estimate	107
9.4.1	Capital Costs	110
9.4.1.1	Reactor Vessel and Thermal Shield	110
9.4.1.2	Primary Coolant Loops	113
9.4.1.3	Blanket Loops	114
9.4.1.4	Miscellaneous Capital Costs	114
9.4.2	Annual Charges	114
9.4.2.1	Fixed Charges on Capital Investment	114
9.4.2.2	Operation and Maintenance Charges	115

9.4.2.3	Fuel Charges	115
9.4.2.3.1	Inventory	115
9.4.2.3.2	Burn-up	115
9.4.2.3.3	Reprocessing and Fabrication	115
9.4.2.3.4	Total Fuel Charges	116
9.4.3	Power Credits and Debits	116
9.5	Tabulations of Cost Estimates	117
9.6	Results of the Estimate	117
9.6.1	Best Basic Cases	118
9.6.2	Power Vs. No-Power	118
9.6.3	Irradiation Time	118
9.6.4	Continuous Processing	119
9.6.5	Cladding of Fuel Elements	120
9.7	Summary	120

SECTION 1 - INTRODUCTION

1.1 Background of the Study

The choice of a "Food Sterilization Reactor" as the subject of an ORSORT summer problem results 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 (1) 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 Tokoyo 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 -- its goal -- sufficient demonstrated progress toward practical radiation sterilization to induce industry to step in. Completion of the necessary development work to establish a food processing industry based upon radiation sterilization would then be the responsibility of private industry.

(1) Nucleonics, Vol. 13 No. 1, p 40 (1955).

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 - minus 0% to plus 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 represented a cost against which the promise of the design could be measured.

1.3 Scope of the Study

The primary aim has been to design a reactor-irradiation system capable of producing a gamma-ray source and using this source to sterilize beef. Irradiation of other foods has not been considered. Production of power has been considered only in the cost estimates which were prepared for several reactor systems.

Information pertaining to the design of a nuclear reactor to supply gamma radiation for food sterilization or other processing is lacking in the literature. In fact, the design of a reactor to be built specifically for this purpose may never previously have been attempted. For this reason the choice of a reactor type to design was not easily made. Indeed, the entire project time could have been spent in developing information and estimates for this choice. The broader requirement of the Quartermaster Corps for an estimate of reactor feasibility prevailed. We have been rather arbitrary, therefore, in the choice of a reactor type upon which to base a conceptual design.

During the course of the study it has become evident that the gamma strength available from a particular reactor type or design would best be utilized if several "tailored" processing lines were built. For example, a heterogeneous reactor could supply gamma radiation from an activated coolant or as decay gammas from used fuel elements retained in a cooling canal. The design philosophy employed in this study has been to supply all of the radiation required in a single processing facility, employing radiation from a single source (such as the activated coolant). It is possible that some economies would be possible through a more exacting design philosophy than the one pursued. However, these design refinements are considered to be outside the scope of this study.

SECTION 2 - CONCLUSIONS AND RECOMMENDATIONS

2.1 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* written by the Quartermaster Corps and listed in section 1. 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 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 processing with radiation from other sources. Dose variation is more readily controlled than when beta rays are used.

2.2 Processing with Coolant Activated in Core or Blanket of Heterogeneous Reactor

A satisfactory way of producing gamma radiation for application to the 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:

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

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 1.6 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.

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

2.3 Recommendations for Future Work

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

a. Use of D_2O in heterogeneous or homogeneous core, with an activated blanket.

b. Activation of an indium coated belt passing through water outside the 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.

SECTION 3 - GENERAL CONSIDERATIONS

3.1 Technology of Food Processing by Irradiation

As a necessary prerequisite to a study of the proposed use of a reactor complex for food processing, one must investigate those aspects of food technology which deal with the behavior of foods under irradiation. When food undergoes irradiation, or cold sterilization as it is sometimes called, some changes occur which may alter the taste, color, shelf life or other qualities of the food.

When beef is subjected to doses less than 100,000 rep. little or no off-color or flavor change can be detected. Although this low level treatment may be effective insofar as prolonging the shelf life of refrigerated foods, sterilization is achieved only on exposure to one to four million rep. According to Schneigert, et al (1), "The characteristics of the odor with higher irradiation dosages are difficult to describe and appear to vary with irradiation dosage. When approximately a two million rep. treatment is used, the odor may be referred to as 'scorched' or 'burnt' while for four million rep. treatment, the odor is similar to that obtained for an overheated meat-cereal combination. When higher dosages are used, the odor of the meat has a 'sweet' characteristic. As far as the color is concerned, it may vary for beef from red (unchanged) to brown, although the texture is not markedly altered."

It is evident that considerable research and development will be required on various means of retarding the undesirable changes accompanying the sterilization of food by irradiation. To date, considerable progress has been made and a

-
- (1) Radiation Sterilization, Reviews of the Literature in Selected Fields, Quartermaster Food and Container Institute for the Armed Forces, Research and Development Command, Quartermaster Corps, U. S. Army.

2.3 Recommendations for Future Work

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

a. Use of D_2O in heterogeneous or homogeneous core, with an activated blanket.

b. Activation of an indium coated belt passing through water outside the 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.

SECTION 3 - GENERAL CONSIDERATIONS

3.1 Technology of Food Processing by Irradiation

As a necessary prerequisite to a study of the proposed use of a reactor complex for food processing, one must investigate those aspects of food technology which deal with the behavior of foods under irradiation. When food undergoes irradiation, or cold sterilization as it is sometimes called, some changes occur which may alter the taste, color, shelf life or other qualities of the food.

When beef is subjected to doses less than 100,000 rep. little or no off-color or flavor change can be detected. Although this low level treatment may be effective insofar as prolonging the shelf life of refrigerated foods, sterilization is achieved only on exposure to one to four million rep. According to Schneigert, et al (1), "The characteristics of the odor with higher irradiation dosages are difficult to describe and appear to vary with irradiation dosage. When approximately a two million rep. treatment is used, the odor may be referred to as 'scorched' or 'burnt' while for four million rep. treatment, the odor is similar to that obtained for an overheated meat-cereal combination. When higher dosages are used, the odor of the meat has a 'sweet' characteristic. As far as the color is concerned, it may vary for beef from red (unchanged) to brown, although the texture is not markedly altered."

It is evident that considerable research and development will be required on various means of retarding the undesirable changes accompanying the sterilization of food by irradiation. To date, considerable progress has been made and a

-
- (1) Radiation Sterilization, Reviews of the Literature in Selected Fields, Quartermaster Food and Container Institute for the Armed Forces, Research and Development Command, Quartermaster Corps, U. S. Army.

number of pre and post-irradiation treatments have been suggested to curtail off flavors and colors. "In general, it may be concluded that pre-freezing and pre-storage of meat, avoiding the presence of oxygen (vacuum packing, sealing in the presence of inert gases), post-irradiation storage, and the addition of certain free-radical acceptors have shown promise in reducing the magnitude of the organoleptic and color changes induced by irradiation treatment (1)."

It should also be noted that exposure to neutron irradiation will favor the production of undesirable odors and colors. It is therefore advantageous to avoid neutron irradiation of the meat if at all possible. Associated with the off-flavor, off-color problem is a possible disturbance of the nutrient value of the irradiated food. However, it is thought that this problem will be overcome as more becomes known about inhibiting the changes which cause off-flavor or odor.

Further discussion of these treatments are beyond the scope of this report and the reader is referred to those references (1,2) dealing more specifically with that phase of food technology.

One of the prime incentives in pursuing the utilization of ionizing radiation for the processing of food is the prospect of dispensing with refrigeration of certain type foods. Although the data are sparse, it has already been demonstrated that exposure to low dosage levels (~ 20000 rep) may prolong the refrigerator shelf life of certain meats about 5 to 20 times.

-
- (1) Radiation Sterilization, Review of the Literature in Selected Fields, Quartermaster Food and Container Institute for the Armed Forces, Research and Development Command, Quartermaster Corps, U. S. Army.
 - (2) S. A. Goldblith, B. E. Proctor, et al., Nucleonics 13, No. 1, 42 (1955).

As pointed out by Lehmann and Laug of the Division of Pharmacology of the Food and Drug Administration (1) the "FDA should approach this new technique with a great deal of conservatism, and yet be conscious of its responsibility not to raise artificial and unrealistic barriers that might impede progress". It is obvious that one cannot accurately predict the safety of irradiated foods until many studies are complete. That is to say, it will be necessary to wait until adequate animal and human feeding programs have been carried out and evaluated.

3.2 Public Acceptance of Irradiated Food

The degree of public acceptance of the irradiation of food will, in a large part, depend on the success of consumer education to food having different cooking requirements. The importance of consumer education to irradiated foods cannot be overemphasized in any discussion dealing with public acceptance.

The most frequent cause of food spoilage is enzymatic and/or bacteriological action. The dose for the destruction of enzymes is approximately 5 to 30 times (2) that required for bacteria. Since a dose of this order of magnitude would render the food inedible, it seems likely that the food will undergo mild preliminary heat treatment prior to irradiation. This general type of treatment would allow products with a wide degree of precooking. Here again, their acceptance would be gained only through effective public education.

In conclusion, it is important to reaffirm the key role of consumer education in gaining public acceptance of irradiated foods or, for that matter,

(1) A. L. Lehman, E. P. Laug, Nucleonics 12, No. 1, 52 (1954).

(2) L. E. Clifcorn, Nucleonics 13, No. 1, 39 (1955).

any new food product. Consequently, on this basis, it is extremely difficult to accurately predict future consumer reaction to irradiated foods.

3.3 Industrial Acceptance

As common with all competitive industries, a new process to be accepted must appear economically attractive when compared with existing processes. Whether this is true of cold sterilization can be shown only by further research and development.

3.4 Other Sources of Sterilizing Radiation

The bactericidal effects responsible for the sterilization of food products are directly a function of the ionization produced within the food. The primary methods for obtaining this ionization are:

1. Secondary electrons from gamma or x-rays, and
2. Highly accelerated electrons or beta particles.

The potential sources of gammas and/or x-rays are:

1. Operating reactors, supplying radiation directly or indirectly
2. Fission product gammas from fuel elements
3. Bremstrahlung from electron accelerators.

The potential sources of beta rays are beta emitting isotopes and beams from electron accelerators such as Linacs, Resonant Transformers, Van de Graaff or Capcitrons.

The comparison between methods can be made on the basis of cost, uniformity of dosage, versatility and time required for a volume of food to obtain the proper dose.

3.4.1 Cost

The cost comparisons shown in Table 3-1 were made on the basis of present day figures and estimates from manufacturers of accelerators on the costs for production up to 40 tons of food per day.

In the case of the fuel elements, the cost were scaled up considering increased plant size only. Because of the already existing need for a "cooling time" before chemical processing of fuel elements, no fuel rental cost was charged to the irradiation facility.

3.4.2 Uniformity of Dosage

High energy electrons deposit energy less uniformly through the product with a maximum energy deposition occurring a short distance in from the surface (1). For the size sample considered, it appears necessary to have at least a 15 mev. beam to obtain depth dosages with 20% tolerance. Swept beam machines give uniformity in the lateral direction.

For gamma rays, tolerances are met with all common sources.

It should be noted that work is being done to show the desirability of having only a surface dose, such as that from low energy beta sources. If surface spores and bacteria are killed, proper sterilization perhaps can be effected without changing anything but the surface quality of the food.

3.4.3 Versatility

Accelerators lend themselves well to maintenance and change of location. Shielding requirements are much less stringent because of the directionability of the beam and the relative absence of neutrons.

(1) F. L. Foster, et al., Nucleonics, Vol. II, No. 10, page 15 (1953).

TABLE 3.I
COMPARISON OF COST FOR IRRADIATION OF 40 TONS OF MEAT
PER 10 HOUR DAY

Method	Radiation	Present Cost	Projected Cost	Projected Cap. Cost
Van de Graaff	3-4 Mev. betas	\$.60/lb. ⁽¹⁾	\$.08 ⁽²⁾	2.5 million dollars
Resonant Transformer	2 Mev. betas ⁽³⁾	\$1.00/lb. ⁽⁵⁾	Not available	Not available
Linac	6 Mev. betas	\$1.00/lb.	Not available	1.7 million dollars
Reactor Elements (40 tons per 24 hour day)	Fission Product Gammas	\$1.00/lb. ⁽¹⁾	\$.08/lb. ⁽⁴⁾	.5 million dollars

(1) Col. Belmont Evans, USQMC, Private Communication. (1955)

(2) F. L. Foster, et al., Nucleonics, Vol. 11, No. 10, page 15 (1953).

(3) Too low energy to meet present specifications, G. E. X-ray reports new model available soon.

(4) Based on power economy supplying free elements. 1000 megawatts (heat) continuous operation needed.

(5) J. A. Knowlton, G. R. Mann, J. W. Ranftl, Nucleonics Vol. 11, No. 11, Page 64 (1953).

X-Rays from Bremmstrahlung were not shown because of the relatively low conversion efficiency from betas.

Reactors are primarily stationary objects. Fuel elements, if produced by power reactors, should be used either at reactor site or at the fuel element processing plant site because of the high cost of shielding in shipment. Low strength facilities utilizing radioactive isotopes however have been made portable.

3.4.4 Time Dose Comparison

Work at MIT (1) is being done to determine if the rate of dose effects the quality of the irradiated food. If any clean advantage is shown for high dose rates, the accelerators will benefit. Accelerators can give the required dose in seconds whereas gamma sources require minutes or hours.

3.4.5 Other Sources

X-ray sources do not now appear to have sufficiently high conversion efficiencies and beta producing isotopes (such as Sr^{90}) appear too dangerous to handle with food.

3.5 Preliminary Calculations

To help visualize the project requirements several initial calculations were made. These were calculations of the processing rate, the theoretical power requirement (based on energy to be deposited in the meat and the processing rate) and the processing volume.

3.5.1 The Processing Rate

The Quartermaster Corps specification is for the processing of 40 tons (80,000 lbs) of meat per 10 hour day. This is equivalent to 133.3 lbs/minute or 1,006 grams/second.

(1) Lt. Col. Belmont Evans, U. S. Q. M. C., Private communication.

3.5.2 The Theoretical Power Requirement (Energy Deposited in Meat)

The theoretical power requirement to give a dose of 2,000,000 rep is:

$$1006 \frac{\text{grams}}{\text{sec}} \times 3600 \frac{\text{seconds}}{\text{hours}} \times 2 \times 10^6 \text{ reps} \\ \times 83 \frac{\text{ergs}}{\text{gm rep}} \times \frac{\text{kw hr}}{3.6 \times 10^{13} \text{ ergs}} = 16.7 \text{ kw}$$

3.5.3 The Processing Volume

The processing volume (volume occupied by the meat being irradiated) is directly related to the processing time. For ten minutes processing time and for an assumed specific gravity of the meat of 0.1 the volume is:

$$1006 \frac{\text{grams}}{\text{sec}} \times 1 \frac{\text{cc}}{\text{gram}} \times 10 \text{ minutes} \times 60 \frac{\text{seconds}}{\text{minutes}} \times 1 \frac{\text{liter}}{1000 \text{ cc}} = 603. \text{ liters}$$

The processing volume is the volume with which the irradiation source may be covered or which, in another method of design, may be surrounded by the source. Utilization of the source strength is highest if the source is covered. In a later section of the report it is demonstrated that the dose and dose variation requirements can be satisfied when the process volume surrounds the source.

SECTION 4

CHOICE OF REACTOR - IRRADIATION SYSTEM

4.1 Introductory Remarks

4.1.1 Criteria for Choice

The type of reactor to design 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 (1), 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

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

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 can not be used where it is created but must be divided between a point of creation and point of use.
- (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.

4.1.2 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 minutes after exposure, if the flavor of the food is spoiled or if particular isotopes (Ca^{45} 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 (see Appendix B for the details) 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 minutes 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 (1) have estimated a permissible thermal neutron flux of about 10⁵ neutrons/cm²/sec for periods of exposure up to a half hour.

4.2 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:

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

(1) Lt. Colonel Belmont Evans, USQMC, Private Communication.

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 if it were operated at several power levels (see ORNL-LR-Dwg. 5936).

<u>Power Level</u>	<u>Water Shield Thickness, cms</u>
1 kw	85
1 mw	140
10 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 minutes 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.

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 power	production efficiency	volume efficiency	utilization efficiency
----------------------	--------------------------	----------------------	---------------------------

4.3 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. If saturated activity had been reached when the reactor were shut down, a decay of 22% in gamma strength would occur in 10 hours.

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 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:

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

theoretical power	production efficiency	time efficiency, core used as gamma radiator 1/2 of time	utilization efficiency
----------------------	--------------------------	---	---------------------------

4.4 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 disadvantage of requiring local fuel processing. This is a chemical operation which it is believed the food processing industry will 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 0.15×5 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 production volume efficiency utilization
power efficiency (assuming no time delay efficiency
between production and
absorption on charcoal)

4.5 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 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 (delayed neutron shielding) of the operation.

Estimated power requirement for this design is:

P = 0.0167 $\frac{195}{5 \times 0.85}$ $\frac{1}{0.25}$ $\frac{1}{0.05}$ = 61 mw.

theoretical prod. eff. volume eff. utilization eff.
pwr. (gaseous fission prods. are not included)

4.6 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. 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 introduced metal as 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

4.7 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:

- (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.

SECTION 5

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 useable 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 5-I 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 in Table 5-I 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 the indium and manganese sulfates was taken at a value somewhat lower than the lowest solubility within the expected operating temperature range.(1). 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 5-I. Except for gallium and perhaps lanthanum and praseodymium, cost is not an important factor bearing upon the choice of nuclide.

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

TABLE 5.I

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	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	7	0.70
						1.8 1.25 0.57		
Bromine	Br	79	51	8.9	4.4h	0.049	100	—
		81	49	2.3	35.5h	0.037 0.547 1.7-2.0 1.35 0.787	100 ~100 0.14 ~100 ~100	
Copper	Cu	63	69	2.8	12.8h 4.3 M	1.34 —	(k capture) —	0.30
Gallium	Ga	69	60	1.5	20 m	—	—	1360.
		71	40	3.4	14 h	1.47 0.83 0.631 0.69 1.05 1.57 2.18	weak ~100 54 5 15 weak 33	
Gold	Au	197	100	96b	2.7d	0.411	100	510.
Iodine	I	127	100	6.3	25 m	0.428	7	—

TABLE 5.I (Cont'd)

Element	Symbol	Isotope	Percent Abundance	Gross Section (barns)	Product half-life	Gamma energy (Mev.)	%	Cost (\$/lb.)
Indium	In	113	4	56b	50d	0.192 0.715 0.548	97 3 3	33.
		115	96	145	54m	1.487 0.406 2.090 1.085 1.274	21 25 25 54 75	
Lanthanum	La	139	100	8.4	40h	2.5 1.6 0.82 0.49 0.335	4 74 15 5 1	
Manganese	Mn	55	100	13	2.6h	3.13 0.81 0.845	12.5 18.75 69	0.32
Praseodymium	Pr	141	100	13	19.2h	0.17 0.134 0.329 0.490 0.624 1.3 1.65 1.53 1.74	—	—
Scandium	Sc	45	100	22	85d	1.12 0.89	98 98	
Tantalum	Ta	181	100	21	117d	1.13 1.22 1.24 0.157 0.165 0.222		41.

TABLE 5.I (Cont'd)

Element	Symbol	Isotope	Percent Abundance	Cross Section (barns)	Product half-life	Gamma energy (Mev)	%	Cost (\$/lb.)
Tungsten	W	182	26	21.b	73.2d	0.134		15.
		184	30					
		186	44					
Silver	Ag	109	48.65	97b 92b	24.5S 270 d	No. 8	81 31 33 17 100	12
						0.885		
						0.935		
						1.389		
						1.516		
						0.656		
Vanadium	V	51	100	4.5b	2.6m 3.7m	1.5 0.25	100 100	40.

SECTION 6 -- DESIGN OF REACTOR CORE

6.1 Reactor Type.

The basic irradiation method chosen was that of an activated material which could be pumped from the reactor to the irradiation volume in a closed system. The neutrons utilized for activation could come from within the core, from the blanket or from a combination of both.

In either case, a choice had to be made between the homogeneous aqueous fuel or a heterogeneous solid fuel reactor. The fully enriched flat plate solid fuel elements with light water moderator were chosen for the following reasons:

- (1) The lack of complexity in pumping and containing materials for the moderator,
- (2) The availability and developed technology of the flat plate elements,
- (3) The desire to absolutely contain all fission products (in particular, the gaseous ones) to avoid any possible contamination of food.

Recognized difficulties of the heterogeneous reactor which might be overcome with the homogeneous system are

- (1) High overload to obtain xenon override (this problem is quite acute on the intermittent process cycle because the cycle requires the reactor to be started up at the very time when the poison effect of xenon is near its peak)
- (2) Higher loading for criticality
- (3) Temperature coefficient not large enough for response control
- (4) Fuel handling problems
- (5) Limited power density

Because of the small fraction of available power which would be utilized in creating gamma rays, consideration was given to the incorporation of a power cycle. This necessitated the use of materials which would withstand high temperatures and pressures and the enclosure of the system in a pressure vessel. The types of cores and the temperature at which they would be operated are included in Table 6-I. The metal to total volume ratios taken are 0.2 for the stainless steel and zirconium systems and 0.41 for the aluminum system. Higher metal to total ratios permit higher power densities but require higher fuel loadings.

TABLE 6-I
TYPES OF REACTOR CORES FOR WHICH CALCULATIONS WERE MADE

Core Material	Position of Activator	Temperature
Stainless Steel	Core and Blanket	450°F
Stainless Steel	Core and Blanket	68°F
Stainless Steel	Blanket Only	450°F
Zirconium	Blanket Only	450°F
Aluminum	Blanket Only	68°F

The stainless is used in the second case (Table 6-I) because the presence of the nuclide to be activated in the core overshadows any absorption disadvantage of the stainless steel, and it is required to resist corrosion by the active nuclide.

The reactor configuration which appeared best is cylindrical. This permits easy assembly of the elements chosen, simple flow patterns for the coolants, and a higher fraction of neutrons lost into the blanket. Special shapes such as disks, hollow cylinders, and flat plates were investigated by comparison with the cylinder on the basis of fractions of neutrons lost to the blanket. They offered no advantages. The comparison of various systems on the basis of power and configuration is shown in Table 6-II.

TABLE 6-II

Comparison of the number of neutrons absorbed in the blanket for various reactor types at an average power density of 80 Kw/liter..... All blanket volumes taken as 500 liters.

Reactor Type	Power	Number of neutrons absorbed to form active nuclides of Indium
Cylinder, 200 cm. high Aluminum, 68° F	17.2 MW	9.7×10^{17}
Cylinder, 100 cm high Aluminum, 68° F	40.0 MW	6.9×10^{17}
Cylinder, 100 cm high Zirconium, 450° F	40 MW	5.2×10^{17}
Cylinder, 200 cm high Zirconium, 450° F	17.2 MW	6.4×10^{17}
Sphere, 40 cm radius Stainless Steel, 450° F	24 MW	3.9×10^{17}
Sphere, 40 cm radius Aluminum, 68° F	24 MW	4.2×10^{17}

6.2 Nuclear Constants

6.2.1 Resonance Escape Probability for Indium Sulfate Solution

The resonance escape probability for a fast neutron in terms of lethargy is written as: *

$$P(u) = e^{-\int_{u_1}^{u_2} \frac{\Sigma_a}{\Sigma_t} du} \quad \text{Eq. 6-1}$$

Since the resonance peaks for indium are widely spaced unique peaks, one can express the escape probability for each peak as:

$$p(u) = e^{-\Sigma_a(E') \Delta E' / \Sigma_t(E') E'} \quad \text{Eq. 6-2}$$

There are four pertinent resonances in indium but one dominant one as shown in AECU-2040. Values of constants or variables are:

$$\begin{aligned} \Sigma_a(\text{th})^{H_2O} &= 0.025 \text{ cm}^{-1} & \Sigma_a(\text{th})^{\text{In}} &= 0.20 \text{ cm}^{-1} \\ \sigma_a(\text{th})^{H_2O} &= 0.66 \text{ barns} & \sigma_a(\text{th})^{\text{In}} &= 145 \text{ barns} \end{aligned} \quad \left\{ \begin{array}{l} \text{represents} \\ \text{max. due to} \\ \text{solubility} \end{array} \right.$$

then,

$$\frac{N^{H_2O}}{N^{\text{In}}} = \frac{\Sigma_a(\text{th})^{H_2O}}{\Sigma_a^{\text{In}}(\text{th})} \cdot \frac{\sigma_a^{\text{In}}(\text{th})}{\sigma_a(\text{th})^{H_2O}} = \frac{0.025}{0.20} \times \frac{145}{0.66} = 27.4$$

$$\Sigma_a(E') = \Sigma_a^{\text{In}}(E') + \Sigma_a^{H_2O}(E')$$

$$\Sigma_t(E') = \Sigma_a(E') + \Sigma_s^{H_2O}(E') + \Sigma_s^{\text{In}}(E')$$

$$\text{thus } \frac{\Sigma_a(E')}{\Sigma_t(E')} = \frac{\sigma_a^{\text{In}}(E')}{\sigma_a^{\text{In}}(E') + \sigma_a^{H_2O}(E') + \frac{N^{H_2O}}{N^{\text{In}}} \times \sigma_s^{H_2O}(E')}$$

$$\sigma_s^{\text{In}} = 2.2b$$

$$\sigma_s^{H_2O} = 40b$$

* Glasstone and Edlund - Elements of Nuclear Reactor Theory, page 164.

The following Table 6-III shows the resonance escape probability for each peak in indium for maximum indium sulphate solubility.

TABLE 6 - III

Resonance Escape Probabilities Indium Sulfate Solution
(For $\Sigma_a^{In}(th) = 0.20 \text{ cm}^{-1}$)

E'	$\Delta E'$	$\sigma_a^{In}(th)$	$\frac{\Sigma_a(E')}{\Sigma_t(E')}$	$\frac{\Delta E'}{E'}$	$p(E')$
1.45 ev.	0.1 ev.	$2.8 \times 10^4 \text{ b}$	0.96	0.069	0.936
3.9 ev.	0.2 ev.	470 b	0.30	0.051	0.985
9.2 ev.	0.6 ev.	130 b	0.106	0.065	0.993
23 ev.	5 ev.	18 b	0.0162	0.217	0.996

Since the maximum indium concentration is set by the solubility, then $\Sigma_a^{In}(th)$
(max) = 0.20 cm^{-1}

$$\text{Thus, } p_{\text{total}}^{min}(E') = p_1 \cdot p_2 \cdot p_3 \cdot p_4 = 0.91$$

6.2.2 Other Constants

Since the systems investigated were in many cases closely related to existing systems and calculations, much use was made of available data. Typical constants used for the ORACLE and hand calculations are:

$$\tau_b = 45.6 \text{ cm}^2 \text{ Age to thermal in the blanket}$$

$$D_{1B} = 1.85 \text{ cm. Diffusion length in blanket}$$

$$P_B = 1 \text{ Resonance escape probability in blanket (non-indium cases)}$$

$$P_C = 1 \text{ Resonance escape probability in core.}$$

$$\Sigma_{T_{2B}} = .035 \text{ cm}^{-1} \text{ Thermal absorption cross section in blanket}$$

$$\tau_{\text{core}} = 48.9 \text{ cm}^2 \text{ Age to thermal in the core}$$

$$D_{1c} = 1.44 \text{ cm Diffusion length in core for fast neutrons}$$

$D_{2c} = .229$ Diffusion length in core for thermal neutrons

$\eta = 2.11$ Number of neutrons per neutron absorbed in U^{235}

$\Sigma_{2c}^M = 0.459$ Non fuel absorption cross section

A table of the other important constants used for various other systems is shown in Table 6-IV.

TABLE 6-IV

NUCLEAR CONSTANTS USED IN REACTOR CORE CALCULATIONS

Constant	S.S., M/T = 0.2 68°F	S.S., M/T=0.2 450°F	Al, M/T = 0.4 68°F	Zr, M/T = 0.2 450°F
$\Sigma_a^M, \text{cm}^{-1}$	.0604	.0437	.01715	.01098
τ, cm^2	35.5	48.9	37.1	44.8
L^2, cm^2	1.05	1.4	1.5	1.87
M^2, cm^2	36.55	50.3	38.6	46.6

6.3 Criticality Calculations - No Nuclide to be Activated in the Core

The determination of critical loading and the fraction of neutrons created in the core which leak into the blanket was determined by each of two methods. They were the one velocity, Fermi age model with reflector savings and the two group, two region calculation. For the two group region calculation, the ORACLE was used with spherical geometry. The ORACLE answers were taken as a basic indication of loading and of the flux pattern in the blanket.

For the cases with no activation in the core, the real model is in close approximation a bare core with some reflector savings. The mathematical simplicity of the Fermi age-one velocity model permitted many systems to be evaluated against each other and was extensively used for comparative purposes. In

the final analysis, a two group-two region calculation for an end reflected bare cylinder would give improved results.

The basic equations for the model chosen are:

$$k = \frac{p\eta\epsilon f}{1 + M^2 B^2} \quad \text{sphere} \quad \text{Eq. 6-3}$$

$$k = \frac{p\eta\epsilon f e^{-B^2\tau}}{1 + L^2 B^2} \quad \text{cylinder} \quad \text{Eq. 6-4}$$

$$= \Sigma_a m / \Sigma_a F \quad \text{Eq. 6-5}$$

$$p\epsilon = 1 \quad \text{Eq. 6-6}$$

where

k is actual criticality

p is resonance escape probability

η is numbers of neutrons from U 235 per absorption in U 235

ϵ is fast effect

f is thermal utilization

M^2 is the migration length which is the sum of the age to thermal and the thermal diffusion length squared

τ is the age to thermal

B^2 is the geometrical buckling of the reactor

L^2 is the square of the thermal diffusion length

α is the ratio of the cross section of all non-fuel components in the reactor to the cross section of the fuel

ν_0 is eigen value for the zero order Bessel function = 2.045

S^2 is the square of the radius of the cylinder

H is the height of the cylinder

R is the radius

V is the volume of the cylinder or sphere

To permit the separation of the leakage from the ends and the side of the cylinder, the criticality equation was written in a slightly different form from that of the sphere:

$$k = \frac{\eta}{1 + \alpha} \frac{e^{-B^2 \tau}}{1 + L^2 B^2} \quad \text{Eq. 6-7}$$

$$B^2 = B_e^2 + B_s^2, B_s^2 = \frac{\gamma_o^2}{\rho^2}, B_e^2 = \frac{\pi^2}{H^2} \quad \text{Eq. 6-8}$$

The total leakage of neutrons from the side of a cylinder is the sum of thermal and fast neutrons which leak out. It is the total number of fission neutrons created times the probability that they will leak out while they are fast plus the total number of fission neutrons created times the probability that they did not leak out while fast times the probability that they will leak out while thermal.

$$\text{Leakage from sides} = \frac{\eta}{1 + \alpha} \left(1 - e^{-B_s^2 \tau} \right) + \frac{\eta}{1 + \alpha} e^{-B_s^2 \tau} \left(1 - \frac{1}{1 + L^2 B_s^2} \right) \quad \text{Eq. 6-9}$$

The primary numbers of interest are the neutrons escaping into the blanket and the volume of the blanket. The buckling was replaced with the volume in both the sphere and the cylinder.

$$B^2 = \frac{\pi^2}{R^2}, \text{Volume} = 4/3 \pi R^3 \quad \text{Eq. 6-10}$$

$$R^2 = \left(\frac{3V}{4\pi} \right)^{2/3}, B^2 = \frac{\pi^2}{\left(\frac{3V}{4\pi} \right)^{2/3}} \quad \text{Eq. 6-11}$$

$$V_{\text{cylinder}} = \pi \rho^2 H, B^2 = \frac{\pi^2}{H^2} + \frac{\gamma_o^2 \pi H}{V_{\text{cyl.}}} \quad \text{Eq. 6-12}$$

$$K_{\text{sphere}} = \frac{\gamma}{1 + \alpha} \left[\frac{1}{1 + M^2 \pi^2 / \left(\frac{3V}{4\pi} \right)^{2/3}} \right] \quad \text{Eq. 6-13}$$

$$K_{\text{cyl.}} = \frac{\gamma}{1 + \alpha} \frac{e^{-B_e} \gamma_e^2 - \gamma_o^2 \pi H L / V}{1 + \frac{L^2 \gamma_o^2 \pi H}{V}} \quad \text{Eq. 6-14}$$

From these criticality equations, the critical loading which is a function of α is determined. In determining the number of neutrons which escape into the blanket, the number created in the core is taken to be a direct function of the power in the core and for constant power the number which escape is plotted for various volumes and core constituents (See Figs. 6-1a, b, d, d, e, f).

$$N_{\text{cyl}} = V \bar{\phi} \Sigma_a F \gamma \left[1 - e^{-\frac{\gamma_o^2 \pi H L}{V}} + 1 - \frac{1}{1 + \frac{L^2 \gamma_o^2 \pi H}{V}} \right] \quad \text{Eq. 6-15}$$

$$G \bar{\phi} \Sigma_a F = E \quad \text{Eq. 6-16}$$

$$N_{\text{cyl}} = \text{Power} \times G \left[1 - e^{-\frac{\gamma_o^2 \pi H L}{V}} + 1 - \frac{1}{1 + \frac{L^2 \gamma_o^2 \pi H}{V}} \right] \quad \text{Eq. 6-17}$$

$$N_{\text{sphere}} = \text{Power} \times G \left[1 - \frac{1}{1 + M^2 \pi^2 \left(\frac{3V}{4\pi} \right)^{2/3}} \right] \quad \text{Eq. 6-18}$$

where E = average power density

$\bar{\phi}$ = average flux

G = neutrons/unit power

The limitation on power for a reactor is primarily determined by the maximum power density at which the core can operate. This maximum power density has been determined in other designs for the materials and cooling methods.

FIG. 6-1c

chosen for this project. The ratio of maximum power density to average was calculated for the bare sphere and for the end reflected cylinder using the 2/3 cosine distribution along the axis of the cylinder.

$$\phi_{\max} = A, \bar{\phi} = \frac{\int_0^{R_0} \int_{-H}^{+H} A J_0\left(\frac{\nu_0 r}{R_0}\right) \cos\left(\frac{\pi k}{4H}\right) 2\pi r dr}{2\pi R_0^2 H} \quad \text{Eq. 6-19}$$

$$\frac{\phi_{\max}}{\bar{\phi}} = \frac{A}{\frac{13A}{\pi^3}} = 2.4 \text{ (cylinder)} \quad \text{Eq. 6-20}$$

$$\phi_{\max} = \frac{A}{B}, \bar{\phi} = \frac{\int_0^{R_0} A \frac{\sin Br}{r} 4\pi r^2 dr}{\frac{4}{3} \pi R_0^3} = \frac{3B}{\pi^2 A} \quad \text{Eq. 6-21}$$

$$\frac{\phi_{\max}}{\bar{\phi}} = 3.25 \text{ (sphere)} \quad \text{Eq. 6-22}$$

Average and maximum power density lines corresponding to various powers and volumes have also been plotted on Fig. 6-1 (a,b,c,d,e,f).

6.4 ORACLE vs Hand Calculations

The calculations with the ORACLE were made for cases with activation in the blanket and activation in the core plus blanket. These calculations were done in spherical geometry using a two group-two region code made by T. Fowler, ORNL. A direct comparison with hand calculation was made, utilizing the same constants and computing the reflector savings on the basis of an infinite reflector. The 60 cm. sphere, stainless steel core gave as a critical loading:

58 Kg for hand calculation

47 Kg for the ORACLE calculation

The reflector savings was calculated as:

$$S = \frac{D_c L_R}{D_R} = \frac{D_c}{(\Sigma_{ar} D_R)} 1/2 \quad \text{Eq. 6-23}$$

The size of the saving was about 2.7 cm. For the calculations to agree exactly the reflector savings would have had to be about 3.4 cm. In reactors calculated with a one velocity-Fermi age model no correction was made for this difference in reflector savings.

The ORACLE calculation gave loading, absorptions in blanket and the flux pattern in the blanket (see Figure 6-2). It should be noted that there is no characteristic peaking of the thermal flux in the blanket. This was due to the high poison content. The relative number of escapes from the blanket and the distribution of absorptions were taken as equivalent for the same thickness blanket in cylinder and sphere.

6.5 Fission Product Poisons

Xenon poisoning is a function of the flux in the reactor and the time after shutdown. For all fluxes, the poisoning reaches a peak about 11 hours after shutdown. For the cases where the reactor is to be operated for only a 10 hour day, the poisoning is nearly a maximum at the time when it is desired to restart. This means that if the reactor is to have full xenon override, a large overload of fuel is necessary. A plot of the poison fraction for various fluxes is given in Glasstone and Edlund, page 337. At 100 kw/liter average power density, the flux is given for various loading in Table 6-V.

TABLE 6-V

FLUX AND POISON FRACTION AS FUNCTIONS OF CORE LOADING

Σ_a (U-235)	Flux (for 100 kw/l)	Maximum poison fraction, W
.02	2×10^{14}	.4
.04	1×10^{14}	.2
.08	5×10^{13}	.1
.16	2.5×10^{13}	.05

FIG. 6-2

ORNL-LR-Dwg.-10270

The poison fraction is used in conjunction with α , the ratio of $\Sigma a_m/\Sigma a_f$ such that a new ratio is obtained.

$$\alpha' = \alpha - W \quad \text{Eq. 6-24}$$

The excess criticality put into the reactor is determined from the new and old alpha.

$$\frac{K_1}{K_0} = \frac{1 + \alpha}{1 + \alpha'} \quad \begin{array}{l} K_0 = \text{old criticality} \\ K_1 = \text{new criticality} \end{array} \quad \text{Eq. 6-25}$$

The new loading is:

$$M' = M \frac{\alpha}{\alpha'} \quad \begin{array}{l} M' = \text{new loading} \\ M = \text{old loading} \end{array} \quad \text{Eq. 6-26}$$

6.6 Fuel Burnout

The fuel burnup is a direct function of the size of the core and the power density. In table 6-VI a comparison is made of the total burnup in a 1000 liter core for various power densities.

TABLE 6-VI

BURNUP IN REACTOR CORE AS FUNCTION OF POWER DENSITY

kw/liter	grams/10 hr day	grams/24 hr day	kg/30-10 hr days	Kg/30-24 hr days
80	40	95	1.2	2.85
100	50	120	1.5	3.6
200	100	240	3.0	7.2
300	150	360	4.5	10.8

The excess k created by the additional loading to compensate for burnout is:

$$\frac{\Delta K}{K} = \frac{\Delta M}{M(1 + \alpha')} \quad \text{Eq. 6-26}$$

A table of the loadings and criticality which must be controlled for several of the reactor types considered is given in Table 6-VII.

TABLE 6 - VII

CORE LOADINGS AND MULTIPLICATION CONSTANTS FOR SEVERAL REACTORS

Reactor	Volume	Power Density	β	Loading	β'	Loading to override Xe	30-10hr. day burnup	K with Xe over load	dk for burn up	Loading	K
Aluminum	800 lit (H=200cm)	100 kw/l	.510	16 kg	.23	36 Kg	2.8 Kg	1.23	.07	38.8 Kg	1.30
Aluminum	1000 (200 cm)	50	.615	16.75	.36	28.6	.75	1.186	.026	29.35	1.212
Zirconium	400 liters (100cm)	87	.664	4.00	.26	10.25	.6	1.32	.021	10.85	1.351
Aluminum	400 Liters H 100 cm.	100	.510	8.05	.21	19.6	.8	1.25	.032	20.4	1.252

6.7 Burnup of Nuclide being Activated

The equilibrium system requires that the total number of decays in the system be just equal to the total creations of active isotopes in the blanket volume. Therefore, there is a continuous reduction in the number of atoms of the poison and consequently in the absorption cross section.

$$\frac{d\Sigma_p}{\Sigma_p} = \frac{d N_o}{N_o} \quad N_o \text{ is total number of indium atoms} \quad \text{Eq. 6-27}$$

To determine the effect of this burnup on the criticality and the makeup rate, the maximum poison content and decay rate were chosen. These corresponded to $\Sigma_p = .2 \text{ cm}^{-1}$ and $S_o = 1.2 \times 10^{12} \text{ decays/cm}^3 \text{ sec}$. The nuclide being activated is indium sulfate. For this value, the fraction lost in a 10 hour day is 3.08×10^{-4} . In a total system of 2000 liters, the makeup per 10 hour day is 180 grams of indium sulfate.

In the case where the indium sulfate appears in the blanket only, the effect of the burnup on criticality is through the reflector savings. If we consider that the only change in this savings is due to the change in the absorption cross section near thermal then,

$$\delta = \frac{D_c}{(D_R \Sigma_{aR})} 1/2 \quad \text{Eq. 6-28}$$

$$\frac{d(\delta)}{\delta} = -1/2 \frac{d\Sigma_{aR}}{\Sigma_{aR}}, \quad d\delta = d(\delta) \text{ is the change in core radius} \quad \text{Eq. 6-29}$$

The effect of a change in reflector savings is to change the buckling. For the Fermi age calculation, the primary effect is on the fast leakage. The differential effects are:

$$\frac{dK}{K} = -2B^2 \Delta B \quad \text{Eq. 6-30}$$

$$B = \frac{V_0}{\rho}, \quad dB = -\frac{V_0}{\rho^2} \quad d\rho = \frac{V_0}{\rho^3} \frac{1}{2} \delta \frac{d\Sigma_a R}{\Sigma_a R} \quad \text{Eq. 6-31}$$

$$\frac{dK}{K} = -\frac{V_0^2}{\rho^3} \delta \frac{d\Sigma_a}{\Sigma_a} \quad \text{Eq. 6-32}$$

For the case of the cylinder, radius 30 cm, aluminum loading, the change in k for the burnup during a ten hour day is 1.24×10^{-5} increase.

If the entire amount of poison is lost from the blanket, the effect is to increase k by 4%.

For a similar calculation from the data on spherical reactors done on the ORACLE, the increase in k for a 50 cm reactor is 2.5% for a complete loss of poison in the blanket.

For the cases where the poison is in the core, dissolved in the moderator, the loss of poison has a much more drastic effect. For a poison loss corresponding to the burnup during a ten hour day operation the ORACLE calculation give 7.4×10^{-3} positive change in k .

If the entire amount of poison is lost from the moderator, the change in k is positive, 67%.

6.8 Temperature Coefficients

For those cases with the poison (nuclide to be activated), in the blanket only, the temperature coefficient of the core is taken to be the temperature coefficient measured on similar systems. However, because the cooling system for the blanket material may be separate from that for the core, calculations were made to determine the effect on the reactor of a change in the temperature of the blanket only.

This blanket temperature coefficient was determined in a manner similar to the effect of the poison burnup in the previous section where the effect on the

reactivity was taken to be that of the change in the reflector savings. The coefficient as calculated with an aluminum cylinder reactor of 30 cm radius is slightly positive, $= 2.7 \times 10^{-5}$. However, it should be noted that the only effect considered was the change in the cross section of the absorbers and in the diffusion coefficient of the water due to the density change. The effect of Doppler Broadening of the indium resonance was neglected.

A calculation was made utilizing the Fermi age equation for the cases where there was poison in the core. The effect of poison is to reduce the clean core temperature coefficient by only a slight amount. The change in the age to thermal is the primary cause for a negative temperature coefficient, and this is only slightly affected by the poison.

A table of the temperature coefficients for the case of interest appears below.

TABLE 6-VIII

TEMPERATURE COEFFICIENTS OF REACTIVITY

Reactor Type	Temperature Coefficient
Aluminum with nuclide to be activated in blanket only	$-1.7 \times 10^{-4}/^{\circ}\text{C}$ (core only)
Zirconium " " " " " " " "	$-2 \times 10^{-4}/^{\circ}\text{C}$ (core only)
Stainless Steel " " " " " " " "	$-1.2 \times 10^{-4}/^{\circ}\text{C}$ (core only)
Blanket w. nuclide to be activated, effect on clean reactor	$+ .27 \times 10^{-4}/^{\circ}\text{C}$

6.9 Control Rods

The maximum excess k is as high as 0.351 for those reactors whose full xenon override is necessary. For a similar aluminum reactor, the reduction in k caused

by eight control rods off center and one center control rod is stated to be 0.6. No calculations were made to determine the effect on neutrons leaking from the reactor, although central rod theory indicates that the effect of a control rod in any position in the reactor is an increase in the number of neutrons leaking.

Because of the increased effectiveness in a control rod which utilizes epithermal neutrons for control, the type recommended is a water filled cadmium cylinder. Some consideration was given to the control of the reactor by varying the water level within this hollow cylinder, but it has the disadvantage that a loss of water in the tube increases the reactivity and therefore does not have inherent safety.

6.10 Equilibrium Time and Residual Activity in Coolant

Because of the finite half-life of the activator, there is a build-up time required before the number of activations is just equal to the number of decays. In the case of indium, which is of primary interest, there is also the effect of the slow buildup of the In^{113} to In^{114} . The half-life of the In^{114} isotope is 50 days and the cross section for creation is 56 barns. The relative abundance of In^{113} in nature is 4.2%.

The relative activation of the long lived isotope is determined by taking the fraction of absorptions which occur at thermal (considering the resonance absorptions) and multiplying by the relative total cross sections, fractional abundance times microscopic cross section.

$$\frac{\text{Creations } \text{In}^{114}}{\text{Creations } \text{In}^{116}} = P f_{113} \sigma_a^{113} / f_{115} \sigma_a^{115} = .01588 \quad \text{Eq. 6-33}$$

If the creation rate of In^{116} is S_0 , corresponding to the decay rate in

the entire system, then the equation for the In^{114} is:

$$\frac{dN_{114}}{dt} = S_0 \times .01588 - \lambda N_{114}, \lambda = \text{decay constant of } \text{In}^{114}$$

$$= .0138 \text{ day}^{-1} \quad \text{Eq. 6-34}$$

The number of atoms which exist at time t is:

$$N_{114} = \frac{S_0}{\lambda} \times .01588 (1 - e^{-\lambda t}) \quad \text{Eq. 6-35}$$

And the relative number of decays is:

$$N_{114} \lambda = S_0 \times .01588 (1 - e^{-\lambda t}) = A(t) \quad \text{Eq. 6-36}$$

After a long time in the reactor, compared with 50 days, the ultimate amount of activity is:

$$A(\infty) = .01588 \times S_0 \quad \text{Eq. 6-37}$$

After a 12 hour operation the fraction is:

$$A(12 \text{ hrs}) = 1.1 \times 10^{-4} S_0 \quad \text{Eq. 6-38}$$

This means that after the long term operation, there is a residual activity in the entire system which amount to 1.5% of the maximum activity. This indicates that it is not feasible to wait for decay in order to do maintenance and that the system must be entirely cleaned out and flushed to reduce the activity to tolerance, or remote methods used.

The equilibrium condition is not reached immediately on start up of the reactor, but is dependent on the 57 minute half-life of abundant In^{116} . In one hour, the activity is approximately half the equilibrium value; in two hours, $3/4$ the value. In setting up the operating schedule, it may be desirable to run the reactor one hour prior to irradiation at a power in excess of the normal operating power, the amount would have to be twice power with a reduction to normal after one hour.

6.11 Optimizing Blanket Volume

The sizes of the reactor and blanket are tightly coupled to the rest of the system, and analytical methods are useful in guiding the choice of size and power.

For the case of indium in blanket only, a relationship between the blanket volume and the volume of the irradiator can be worked out for a fixed total number of activations in the blanket. If:

n = the ratio, V_{irr}/V_{bl}

f = the fraction of blanket volume which must be added to the total volume for piping, heat exchange, etc.

V_{irr} = the volume of the irradiation facility, cm^3

A = the area of the irradiation facility, determined by the number of passes by the meat, the process rate, and the process time, cm^2

V_B = the volume of the blanket, cm^3

S_o = the activity (disintegrations/sec cm^3) in the irradiator

S_o^* = the activation rate or creation of active nuclei in the blanket per second per cc

S_a = the activity per unit area at the surface of the irradiation volume, disintegration/sec cm^2

t = the thickness of the irradiation volume, cm

λ = mean free path of gammas in the irradiation volume, cm

T = total activations in blanket

Then the surface strength of the irradiation source as a function of volume is approximately: (integration of $S_a = S_o \int_0^t e^{-\lambda t} dt$)

$$S_a = \frac{S_o}{\lambda} (1 - e^{-t/\lambda}) \quad \text{Eq. 6-39}$$

Because of volume dilution of the activity the relation between S_o and S_a is:

$$S_o = \frac{S_o^* V_B}{V_B + V_{irr} + f V_B} \quad \text{Eq. 6-40}$$

$$S_o^* V_B = T \quad \text{Eq. 6-41}$$

$$t = \frac{V_{irr}}{A} \quad \text{Eq. 6-42}$$

$$S_a = \frac{T(1 - e^{-V_{irr}/A\lambda})}{\lambda(V_B + V_{irr} + f V_B)} \quad \text{Eq. 6-43}$$

$$V_{irr} = \eta V_B \quad \text{Eq. 6-44}$$

$$S_a = \frac{T}{\lambda V_B} \frac{(1 - e^{-\frac{\eta V_B}{A\lambda}})}{(1 + f + \eta)} \quad \text{Eq. 6-45}$$

This gives a relation between the surface activity, the blanket volume and the ratio of blanket volume to irradiation volume. For a fixed blanket volume, the surface activity would go to zero for n equal to zero or infinity, therefore there is at least one extremum between these points. By differentiation:

$$\frac{dS_a}{dn} = \frac{T}{\lambda V_B} \left\{ \frac{V_B}{A\lambda} \frac{e^{-nV_B/A\lambda}}{(1 + f + n)} - \left[1 - \frac{e^{-nV_B/A\lambda}}{(1 + f + n)^2} \right] \right\} = 0 \quad \text{Eq. 6-46}$$

and the relation for a given volume is:

$$(1 + f + n) \frac{V_B}{A\lambda} = e^{-nV_B/A\lambda} - 1 \quad \text{Eq. 6-47}$$

There is no simple solution for n as a function of blanket volume so the relationship was plotted for characteristic values and a sample of such a plot is shown in Figure 6-3. This would permit getting approximate ratios between

FIG. 6-3

ORNL-IR-Dwg.-10271

blanket and irradiation volumes for best utilization of the neutrons coming into the blanket.

The distribution of activations in the blanket is not uniform but follows a function of the slowing down of neutrons. If one considers that the neutron is captured at approximately the position it reached thermal energy, or reached the indium resonance energy, the form of the function is near exponential. In the two group - two region theory it is the sum of hyperbolic functions. Using the age of fission neutrons in water, the number of neutrons which escape from a 16 cm thick blanket is 14.4%. Using the data from Lid Tank measurements which gave a relaxation length for neutrons of 8.3 cm., the percentage which escape is 14.6%. Later work with the ORACLE, based on the 16 cm blanket and a 60 cm radius spherical core gave 20% escapes. This discrepancy is taken to be due to the difference in the angular distribution of neutrons from the face of the core. The core distribution is more peaked in the forward direction compared with the plane sources calculated.

This exponential creation of activity in the blanket indicates that possibly there is a "self-dilution" factor in having coolant in the outer portion of the blanket. This is shown in Figure 6-4 where the relative effectiveness of the outer layers of the blanket depends on the ratio of V_{irr}/V_B . The higher the ratio, the more effectiveness is gotten from the outer layers.

The variation described indicates that if, after a facility has been constructed, it is desired to operate at less than maximum throughout, greater efficiency can be obtained by reducing the blanket thickness.

FIG. 6-4

ORNL-LR-Dwg.-10272

SECTION 7 - THE IRRADIATION FACILITY

7.1 Introduction

The specifications of the irradiation facility are based on the general requirements laid down by the U. S. Quartermaster Corps. (1) 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".

7.2 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. A quantitative evaluation of the edge effect is treated in 7.3.

The 6" x 16" x 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

(1) See 1.2 of Section 1 for discussion of these requirements.

penetration depth. Results of some of the calculations for both one-side and two-side irradiations are shown graphically in Fig. 7-1. Based on the results of Fig. 7-1 the cartons must pass the irradiation volume single file and with each of two sides in turn closest to the source in order to keep the dose within the specified 25% overdose. Fig. 7-2 shows the selected geometry for the process line. The dose is equivalent to Case (1) in Fig. 7-1.

7.3 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 (that shown in Fig. 7-2) 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 shown in Fig. 7-3.

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

Z = distance between source and meat

l^s = source half-width

K = (1 + variation in dose)

l = meat coverage half-width

* For derivation of Equation 7-1 see Appendix A

FIG. 7-1

FIG. 7-2

FIG. 7-3

ORNL-LR-Dwg.-10275

The plots of the right and left-hand sides of equation (7-1) in Figure 7-3 demonstrate how the appropriate amount of overlap was chosen to keep the dose variation within the required limits. For example, if the conveyor system is 24 inches from the source and a 5% dose variation is allowed, then an overlap in the source of 26.5 cm is needed as shown by the intersection of the 5% curve with the $\tan^{-1} \frac{1}{24}$ curve.

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 as in Figure 7-4.

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

σ_o = surface source strength

S_o = volume source strength

t = source thickness

a = source radius

E_3^P = see Placzek Functions(1)

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 7-1.

$$V_{ir} = A \text{ meat } \left(1 + \frac{L}{40}\right) t \quad S_o = \frac{\sigma_o}{t} \frac{1}{(\sigma_o/S_o t)} \quad \text{Eq. 7-3}$$

V_{ir} = irradiation volume

A = meat area

L = overlap of source

σ_o = surface source strength

t = source thickness

Since the processing or holdup time enters directly into the required S_o .

(1) N. R. C. No. 1547, The Functions $E_n(x) = \int_1^\infty e^{-xu} u^{-n} du$, G. Placzek.

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

FIG. 7-4

ORNL-IR-Dwg.-10276

Relationship Between Specific Activity and Volume of Source

Passes	t (cm) Source Thickness	V(liters) Source Volume	So $\frac{\text{mev}}{\text{cm}^3 \text{sec.}}$ 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

FIG. 7-5

ORNL-IR-DWG.-10277

and irradiation volume, one can read the related values of S_o and V_{irr} in Fig. 7-5 for various holdup time by reading into the ordinate and abscissas the holdup time used. Figure 7-5 was prepared by use of Equation 7-4.

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

τ = holdup time in minutes

L = overlap

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

In order to compare the utilization of the gamma energy at different activity levels, Table 7-II was prepared with the utilization, U, obtained from:

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

The results of Table 7-II are shown graphically in Figure 7-6.

7.4 Mechanical Design of Source Volume and Food Carrier

The design of the source volume is based on the assumptions made in Section 7.2. For a 10 minute processing time and arrangement as shown in Figure 7-2, 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 7-7. The configuration used in Figure 7-7 is based upon the plan shown in Nuclear Engineering - Part III, "Design

TABLE 7-II

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

Passes	t_s (cm)	V_s liters	$So \frac{\text{mev}}{\text{cm}^3 \text{ sec}}$	SoVs	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

FIG. 7-6

ORNL-IR-DWG.-10278

FIG. 7-7

PLAN VIEW
10 MIN. IRRADIATION FACILITY

CRNL LR-DWG.-10279

of a Pork-Irradiation Facility Using Gamma Rays to Break the Trichinosis Cycle", H. J. Gomberg, et al.

7.5 Shielding and Refrigeration of Irradiation Facility

Using $S_0 = 10^{13} \frac{\text{decays}}{\text{cm}^3\text{-sec}}$, 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 to 0.1 mr/hr. It is found by standard shielding calculations (1), using buildup factors, that 5 feet of barytes concrete is needed. The geometry of the shield chosen is illustrated in Figure 7-7.

In order to preserve the natural taste of beef, it is best to irradiate while frozen (2). 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

(1) See Apex 176

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

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

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

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 feet concrete wall the heat removal was calculated and resulted in a refrigeration capacity of 4.1 tons for the $9' \times 57' \times 30'$ overall irradiation cell. The capacity need not be this high if, as is likely, a larger refrigerated storage room surrounds the irradiation cell.

7.6 Economics of the Irradiation System (See Table 7-III, 7-IV, and Fig. 7-8)

7.6.1 Concrete Shielding and Housing

The amount of concrete used in the shielding and cell construction is as shown in Fig. 7-7 with the calculated amount equal to 494 cubic yards. The installation of the concrete was figured at two extremes, \$50 and \$120 per cubic yard (1). Excavation for the facility was estimated to be 232 yards³ at \$2.70/yd. The total cost is shown in Table 7-III.

7.6.2 Conveyor Cost (1)

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. A cost of \$21.10 per foot was calculated. The total monorail length for a processing time of 10 minutes was estimated to be 190 feet.

7.6.3 Source Slab

Based on a cost of \$5/lb for fabricated and installed stainless steel,

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

TABLE 7- III

ESTIMATED COST FOR 10 MINUTE IRRADIATION FACILITY

	Part at \$120 yd.	At \$50 yard
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

TABLE 7 - IV

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 @ \$120/yd.	concrete @ \$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

FIG. 7-8

ORNL-IR-Dwg.-10280

a value was arrived at for the cost of 5' x 6' x 1', 1/5" thick tank.

7.6.4 Refrigeration Costs (1)

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

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

SECTION 8

DESIGN OF COMBINED REACTOR - IRRADIATION SYSTEMS

8.1 Introductory Remarks

Following the analysis and design of the irradiation facility and the ORACLE and other calculations of several reactors, it was necessary that workable reactor-irradiation systems be developed. Where the reactor and irradiation facility are combined, the result is a dilution of the activity created in the reactor core or blanket by additional volumes in the irradiation facility and in the piping and heat exchange equipment. This dilution effect has been represented by the volume efficiency term in earlier discussions.

Both "clean" core (activity created in blanket) and "dirty" core (activity created in core) designs have been made. Features of the "dirty" core and "clean" core operations, as listed in Table 8-1, appear to indicate an advantage for the "clean" core operation. However, cases of both types are cost estimated in Section 9.

Of thirty-eight two group - two region calculations made by the ORACLE, only fifteen were found to be capable of satisfying the requirements of the combined reactor-irradiation system. In summary the results are found on Table 8-1.

TABLE 8 - I

Features of "Dirty Core" and "Clean Core" Operation

<u>"Dirty Core"</u>		<u>"Clean Core"</u>
1. Activated solution sees high neutron flux.		1. Activated solution sees low neutron flux.
2. Concern about salting on fuel elements.		2. Core operation clean — thus conventional
3. High core loading		3. Low core loading.
4. High piping and heat exchange volumes in irradiation loop.		4. Low piping and heat exchange volumes in irradiation loop.
	<u>Reactors Calculated</u>	<u>Reactors Satisfying Requirements</u>
Manganese sulfate in "dirty" core	19	8
Manganese sulfate in Blanket - "clean" core	14	3
Indium sulfate in Blanket - "clean" core	4	4

Of the "dirty" core cases which were shown to satisfy the requirements of the combined reactor-irradiation system, six are excessively high uranium loading. From two-group two-region calculations made on the ORACLE, only nine reactor-irradiation systems were cost estimated in Section 9.

8.2 Bases of Calculations

In the reactor designs, the effects of fuel element cladding metal, metal to total volume ratio, reactor radius, poison cross section and temperature were studied. In order to compare the reactor designs and to pick the "best"* reactors (in association with the irradiation facility) several design assumptions were made. These are:

*No optimization has been made but we believe that the "best" reactor designs are near the minimum design (considering size, power and cost) possible with activation in the blanket.

1. Temperature rise in active fluid while in reactor core or blanket-----
100°F.
2. Size of system piping - choose so that velocity in pipe is 10 ft/sec.
3. Length of system piping ---- 100 ft.
4. Holdup volume in flash cooler ----- assume to be 1 ft³ per megawatt.
5. In cases where fluid is activated in blanket assume 2% of total heat
produced in core is removed in blanket.

8.3 Method of Calculation

To illustrate the method of calculation which has been used in combining the reactor and irradiation facilities the calculation for case 36 is shown in detail below. This case is one in which indium sulfate is activated in the reactor blanket. The macroscopic absorption cross section for thermal neutrons is 0.20 for the poison. The reactor radius is 40 cms and the shell thickness between core and blanket, 1 cm. The cladding material is stainless steel.

8.3.1 Flux at Center of Reactor

Using data from Table C of Appendix C and following the methods outlined in CF-51-10 and CF-53-2-134, a thermal neutron flux at the center of the reactor was calculated to be: (a maximum power density at the center of the core is assumed to be 280 kw/liter).

$$\phi_p(0) = \frac{0.28 \text{ MW/Liter} \times 3.38 \times 10^{16} \text{ fission/MW sec}}{1000 \text{ ccs/liter} (0.06 \times 0.83) \text{ fission/cm neutron}} = 1.9 \times 10^{14} \text{ neutrons/cm}^2 \text{ sec}$$

8.3.2 Reactor Power (assuming Max 280 kw/liter at reactor center)

$$P_c = \frac{1.9 \times 10^{14} \times 4\pi \times 0.06 \times 0.83 \times 19.31}{\phi(0) \times 3.38 \times 10^{16} \times 0.106} = 37.7 \text{ MW}$$

Σ_{2c}^F Σ_{2c}^T

8.3.3 Flux Ratio (at power/normalized)

$$\frac{\phi_p(0)}{\phi(0)} = \frac{1.9 \times 10^{14}}{0.017} = 1.118 \times 10^{16}$$

8.3.4 Neutron Captures in Indium per Second

$$= \underbrace{(2.12 + 0.917 \times \frac{0.20}{0.225})}_{\text{normalized captures}} \times 4\pi \times 1.118 \times 10^{16} = 4.13 \times 10^{17} \frac{\text{captures}}{\text{sec.}}$$

8.3.5 Blanket Volume

$$= \frac{4\pi}{3} ([R + T]^3 - R^3) = 4.19 (185,000 - 69,000)$$

$$= 486,000 \text{ cm}^3 = 486 \text{ liters}$$

8.3.6 Heat Removal

$$= 0.02 \times 37.7 = 0.75 \text{ MW heat removed in irradiation loops.}$$

8.3.7 Flow Rate

$$C_p \text{ of indium sulfate solution} = 0.74 \text{ Btu/lb } ^\circ\text{F}$$

$$\text{lbs/gallon} = 8.31 \times 1.5 = 12.54$$

$$= \frac{0.75 \text{ MW} \times 0.342 \times 10^7 \text{ Btu/hr MW}}{60 \frac{\text{minutes}}{\text{hour}} \times 100^\circ\text{F} \times 0.74 \frac{\text{Btu}}{\text{lb}^\circ\text{F}} \times 12.54 \frac{\text{lbs}}{\text{gallon}}} = 46 \text{ gpm.}$$

8.3.8 Pipe Volume

Pipe size required is 1 1/4"

It contains in 100 ft ----- 30 liters

8.3.9 Flash Cooler Volume

= 70 liters (smaller sizes probably require more than 1 ft³/megawatt)

8.3.10 Total Volume Exclusive of Irradiation Volume

= 586 liters

8.3.11 Table of S₀ Values (decays/sec cm³) for Several Irradiation Volumes

(Power density at center of core = 280 kw/liter)

<u>Irradiation Volume(liters)</u>	<u>Total Volume</u>	<u>S₀ (Indium)</u>	<u>Required Equivalent S₀ (Manganese)</u>
100	686	6.02×10^{11}	9.15×10^{11}
200	786	5.25×10^{11}	7.98×10^{11}
300	886	4.67×10^{11}	7.10×10^{11}
500	1086	3.8×10^{11}	5.77×10^{11}
1000	1586	2.6×10^{11}	3.95×10^{11}
2000	2586	1.6×10^{11}	2.42×10^{11}

8.3.12 Graphical Solution

The values in the section just above may now be plotted as a curve of irradiation volume versus S₀. In Section 7 describing the irradiation facility, its requirements were also graphically expressed as irradiation volume versus S₀. Thus, if the two curves are superimposed on the same graph, points of intersection represent situations for which the capabilities of the reactor-irradiation system meet the requirements of the irradiation facility. Figure 8-1 shows the graphical solution for Case 36. At 280 kw/liter power density the minimum processing time is 60 minutes. By repeating the S₀ vs irradiation volume calculations the minimum power density and power requirements at 100

minutes processing time can be found to be: Power = 31 MW

Power density = 230 kw/liters

8.3.13 Efficiencies

To check the solutions obtained, an analysis may be made of the efficiencies involved and a power requirement estimated. This should check the power requirement obtained.

For the 100 minute processing time:

Production efficiency

$$\text{Captures per fission} = 2.5 \times \frac{2.935}{23.05} = 0.319$$

$$\text{Efficiency} = \frac{0.319 \times 2.48 \frac{\text{Mev}}{\text{decay}} \times 100}{195} = 0.405\%$$

Utilization efficiency

Irradiation volume = 1500 liters

$$S_0 \text{ (Indium)} = 1.64 \times 10^{11}$$

Power available in source =

$$1,500,000 \times 1.64 \times 10^{11} \times 2.48 \times \frac{1}{6.24 \times 10^{15}} = 98 \text{ kws}$$

Theoretical requirement = 16.7 kw

$$\text{Efficiency} = \frac{16.7 \times 100}{98} = 17\%$$

Volume efficiency

$$\frac{\text{Irradiation volume} \times 100}{\text{Total volume}} = \frac{1500 \times 100}{2086} = 72\%$$

$$\text{Power} = 0.0167 \times \frac{1}{0.00405} \times \frac{1}{0.72} \times \frac{1}{0.17} = 33.7 \text{ MW}$$

Theoretical	Production	Vol.	Util.
Power	Efficiency	Eff.	Efficiency

FIG. 8-1

ORNL-IR-Dwg.-10281

8.4 Workable Reactor - Irradiation Systems

8.4.1 Activation of Manganese in Blanket

Fifteen reactor-irradiation systems were found to be workable among the reactor cases obtained from ORACLE calculations. Result of graphical solutions in three "clean" core cases in which manganese was activated in the blanket are shown in Table 8-II. Examination of these results reveals that while these cases are workable they require a large amount of power as compared to "clean" core cases using indium. They have not been cost estimated.

8.4.2 Activation of Manganese in Reactor Core

Eight systems in which manganese is activated in the reactor core have been designed and the results shown in Table 8-III. Only two of these systems were cost estimated in Section 9. The others require excessively high fuel loadings.

8.4.3 Activation of Indium in Reactor Blanket

Results for systems operating with a clean reactor core and with indium sulfate in the blanket are shown in Table 8-IV. Four of these systems were calculated from ORACLE results. Others were designed around reactors calculated by using a one velocity Fermi age model as discussed in Section 6 of this report. The lowest reactor power requirements are for systems in which the power (heat) is to be "dumped". However, the power production cases were considered possibly attractive and were cost estimated, considering credits which could be obtained from sale of power.

Use of D_2O in either a heterogeneous or homogeneous core (cases 45 and 46) results in systems in which the power requirement is low.

TABLE 8 - II
SUMMARY OF "CLEAN CORE" RESULTS (16 cm BLANKET - Solution
of Manganese Sulfate)

Case No.	26	27	33
Reactor Type	Stainless Steel		Package Power
Power Producer	Yes		
Metal to total Vol. Ratio	0.20	0.20	0.20
Shell Thickness	1	1	5
Moderator	H ₂ O	H ₂ O	H ₂ O
Blanket Poison Σ , Gm ⁻¹	0.5	0.5	0.5
Reactor Radius	60	80	80
100 Minute Process Time Power, MW Power Dens, Max. $\frac{\text{kw}}{\text{liter}}$	133 280	301 247	374 280
Max. Power Density, 280 kw/Liter Power, MW Processing Time, Mins.	133 100	341 70	374 100
Critical Fuel Loading, Kg	25.2	57.5	56.7

TABLE 8-III

SUMMARY OF "DIRTY CORE" RESULTS SOLUTION OF MAGANESE SULFATE THROUGH
CORE ONLY

Case No.	14	16	10	11	2	3	5	6
Reactor Type	Stainless Steel - Package Power							
Power Producer	No							
Moderator and Coolant	H ₂ O							
Metal to Total Vol. Ratio	0.10	0.20	0.10	0.20	0.10	0.10	0.20	0.20
Poison Cross Section Σ, cm^{-1}	0.5	0.5	0.05	0.05	0.10	0.50	0.10	0.50
Reactor Radius	50	50	70	70	90	90	90	90
100 Minute Process Time Power, MW. Power Density, Max. $\frac{\text{kw}}{\text{liter}}$	27 150	42 230	114 234	120 245	50 50	35 35	75 75	50 50
Max. Power Dens., 280 kw/liter Power, MW Processing time, Mins.	50 42	51 60	136 65	137 72	281 25	279 18	283 35	280 20
Fuel Loading, Kg.	176	166	75.5	88.8	234	881	283	824

TABLE 8-IV

SUMMARY OF "CLEAN CORE" RESULTS (16 cms. Thick Blanket Solution of Indium Sulfate)

Case No.	37	38	35	36	39	40	41	42	43	44	45	46
Reactor Type	Stainless Steel- Package P.				Zirconium-Pack. P.				Aluminum - MTR		CP-5	HRT
Power Producer	Yes				Yes				No		No	No
Metal to Total Ratio	0.2				0.2				0.41		0.34	—
Moderator	H ₂ O				H ₂ O				H ₂ O		D ₂ O	D ₂ O
Blanket Poison, Σ , cm ⁻²	0.05	0.20	0.05	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Reactor Radius	60	60	40	40	40	60	80	40	60	80	60	80
100 Min. Process Time												
Power, MW	93	64	39	31	23	55	112	17	39	80	16.9	15.6
Power Dens, Max. $\frac{\text{kw}}{\text{liter}}$	224	160	280	230	280	196	171	207	140	122	60.6	24
10 Min. Process Time												
Power MW	—	—	—	—	—	—	—	—	—	184	38	29
Power Density $\frac{\text{kw}}{\text{liter}}$	—	—	—	—	—	—	—	—	—	280	136	44
Fuel Loading, Kg	26.5	26.5	9.5	9.4	4.3	10.7	22.8	5.5	11.9	24	7.5	6.4

In addition, the ten minute processing time specification appears to be readily met. Cost estimates made in Section 9 indicate that processing becomes cheaper as processing (holdup) time increases. Therefore, D_2O cases have not been carefully examined. This may be an area for fruitful future work.

A correlation exists between the number of indium activations required in the indium blanket and the volume of the blanket. This correlation is shown in Figures 8-2 and 8-3 and was obtained from the "clean" core cases calculated by the ORACLE. Figure 8-4 extends the correlation to other processing times. Through use of the correlation the results for cases 39 through 46 in Table 8-IV were obtained.

FIG. 8-2

ORNL-IR-DWG.-10282

FIG. 8-3

ORNL-IR-DWG.-10283

FIG. 8-4

ORNL-IR-DWG-10284

SECTION 9 - THE COST ESTIMATE

9.1.0 Purpose

The aim of this analysis is to estimate the cost (per pound of meat irradiated) of the reactor powered irradiation facilities described herein. The desired result of design efforts has been to produce at least one system with a meat processing cost in the range of two (2) to five (5) cents per pound. These figures were suggested by the Army Quartermaster Corps and are established by expected savings in refrigeration, storage, and processing costs now charged to other processes.

9.2.0 Scope

This report covers nineteen reactor powered irradiation systems. Of these, eleven are combination irradiation electrical generating plants, while the eight remaining cases are irradiation systems only.

Within the framework just noted there are several cases which illustrate the effect of certain variations from basic plant operating conditions. These operating conditions and variations therefrom are described later in this section.

9.3.0 Systems (See Figures 9-1, 9-2)

9.3.1 Power Generating Cases

The plants which include power generation are closed circuit high pressure systems. The major reactor system loops are the primary coolant, or core circuit loop, and the blanket loop. Power generation steam is produced in a closed heat exchanger which is part of the primary coolant loop. In two (2) cases the activated element is manganese contained in aqueous solution in

the primary coolant loop. These are called "Dirty Core" cases. The other systems are designated "Clean Core" and contain indium as the active element, but in the blanket circuit. Three of the indium-clean core cases have zirconium clad fuel elements: all other systems use stainless steel. These materials were selected for the temperatures required for power generation.

The irradiation facility source duct is located, naturally, in the activated loop. Blanket heat is removed in a blanket loop heat exchanger.

9.3.2 "No Power" Cases

These are low pressure systems using a flash cooler and condenser to dissipate heat, in place of the closed heat exchangers used in the power system cases. Major reactor system loops are otherwise similar to those previously described.

The same two manganese "Dirty" core cases described above are also included here, minus, of course, the power generating facility.

Six cases remaining are indium-clean core systems.

All reactors except the manganese systems use aluminum clad fuel elements. The latter use stainless steel to provide corrosion resistance required with the activated solution. Aluminum is suitable in the "clean" core cases due to the lower operating temperatures of the no-power systems.

9.4.0 Basis of the Estimate

Methods and data used in obtaining capital costs and annual charges are described in the sections which follow.

FIG. 9-1

**SIMPLIFIED FLOW DIAGRAM
CORE LOOP WITH POWER PRODUCTION**

FIG. 9-2

9.4.1 Capital Costs

Capital costs cover all material and labor, including labor of installation or erection. Allowance for contingencies and engineering and contractor's fees are all taken as 10%.

9.4.1.1 Reactor Vessel and Thermal Shield

The cost estimation of the reactor vessel was based on calculating the weight of material required and then computing the cost.

In those cases where power was being produced, the pressure vessel shell thickness was calculated in accordance with Section UG-27 of the ASME Standards for Unfired Pressure Vessels, 1952 as follows:

$$t = \frac{PR}{SE - 0.6P}$$

where t = minimum required thickness of shell plate, cm.

P = 1200 = design pressure, psi

R = inside radius of shell, cm

S = 16000 = maximum working stress, psi

E = 0.85 = efficiency of longitudinal joint

It should be noted at this point that these are the specifications for a cylindrical pressure vessel whereas most of the core nuclear calculations were based on a spherical reactor. It was felt that, for purposes of cost estimation, a more realistic cost figure could be arrived at by assuming a geometric shape that would be compatible with existing fuel element lattice arrangements and reloading techniques. (The advantages to be gained by this assumption has been borne out by calculations reported in an earlier section). It was for these reasons, then, that the spherical core was approximated by a right cylinder

(that is, a cylinder with its height equal to its diameter) having a diameter equal to the diameter of the sphere. Note: This represents an increase in the volume of the active core of 50%).

Since the ASME Standards do not make allowance for corrosion or thermal stress, all shell thicknesses so calculated were increased 1 in. as suggested in Ref. (1). The weights of the top and bottom heads were calculated considering them as hemispherical heads.

The general configuration of the vessel, showing the parts on which the weight calculations were based is shown in Figure 9-3.

For the non-power cases, a similar technique was used with the exception that a vessel wall thickness of 1 in. was assumed in all cases.

The cost figures were based on the following rates:

Zirconium	\$50/lb (2)*
Stainless clad carbon steel	\$1.50/lb (2)*
Aluminum	\$0.22/lb (3)
Stainless steel	\$3.00/lb
Thermal shield (either solid stainless or carbon steel)	\$1.00/lb (2)*

* add 25% for installation charges.

-
- (1) ORNL CF 54-10-111 Cost Estimating Information, TBR Memorandum No. 4, M. Lundin.
 - (2) ORNL CF 54-10-111 Cost Estimating Information, TBR Memorandum No. 4, M. Lundin.
 - (3) Private Communication, M. Lundin.

FIG. 9-3

ORNL-LR-Dwg.-10287

SIMPLIFIED GEOMETRIC ARRANGEMENT
OF REACTOR VESSEL FOR COST
ESTIMATING PURPOSES

9.4.1.2 Primary Coolant Loop

In the power systems, the primary coolant loop is a high pressure closed system, consisting of a main heat exchanger and steam generating system, a pressurizer system, a dump tank circuit, pumps, and piping.

Heat exchanger and steam drum at \$5.00 per kilowatt of heat

Pressurizer system - extrapolated from cost for similar equipment

Pumps and motors - from curves giving average pump cost (1)

Tanks - as stainless steel at \$5.00 per pound

Piping - pipe costs were extrapolated from costs for a similar loop by the ratio of the diameters to the 0.6 power, and a correction for weight.

$$\text{Cost of pipe} = (\text{Ref. costs}) \left(\frac{\text{New Dia.}}{\text{Old Dia.}} \right)^{0.6} \left(\frac{\text{new unit weight}}{\text{old unit weight}} \right)$$

Valves, included as 25% of piping costs.

The turbo-generator plant, including electrical equipment, was evaluated at \$106.00 per kilowatt of capacity.

In the "no-power" cases a flash cooler and surface condenser replace the heat exchangers and steam generator of the high pressure systems. The flash cooler, a tank with inlet water spray nozzles, was priced as stainless steel at \$5.00 per pound. The surface condenser was charged at \$35.00 per square foot(1). These costs are considered sufficient to cover piping between the vessels. Other pipe, valves, and pumps were charged in the same manner described above. Since pump cost data is based on average costs for all types, no correction was made for change of design head.

(1) Cost Estimate Information, TBR Memo No. 4, ORNL-54-10-111.

9.4.1.3 Blanket Loops

Blanket loops were evaluated in the same way as the primary coolant loops, using the same sources of information. Since blanket heat dissipation is only a small fraction (2% assumed) of the total, all components are naturally much smaller than those of the primary loop.

9.4.1.4 Miscellaneous Capital Costs

Installed cost of shielding concrete was taken at \$120 per cubic yard. Examination of installed cost of concrete for various installations showed a variation from about \$50 to \$170 per yard. The figure used here is that stated for ORNL ordinary concrete cost (1).

Building and site development was computed from the relation below:

$$\text{Cost} = \$500,000 + 5,000P, \text{ where } P \text{ is in MW of reactor heat.}$$

The costs for other items, such as crane, stack, core handling equipment, process instrumentation, and various auxiliary cooling systems were entered as lump sums, their magnitudes estimated after a survey of costs for similar equipment.

9.4.2 Annual Charges

9.4.2.1 Fixed Charges on Capital Investment:

Annual fixed charges used herein are as follows:

	<u>Depreciating Equipment</u>	<u>Land %</u>
Depreciation	3	-
Return on Investment	6	6
Taxes, Insurance	<u>6</u>	<u>6</u>
TOTAL	15%	12%

(1) Nucleonics - June 1955.

The three percent charge reflects a twenty year depreciation period. Land was valued at \$500 per acre for 500 acres, or \$250,000. Value and area of land has been arbitrarily selected.

9.4.2.2 Operation and Maintenance Charges:

These were assumed as 25% of total annual fixed charges on capital. Similar charges on medium sized modern steam plants range from 18% to 20%. ORNL 1640 suggests a figure of 20% for this item.

9.4.2.3 Fuel Charges

9.4.3.1 Inventory

Critical loadings for the various reactors were obtained from ORACLE two group, two region (spherical) and from computations using Fermi Age theory applied to a bare reactor. For purposes of cost estimation, twenty-five percent of the critical mass was assumed to be sufficient excess mass required for poison and burnup. A value of twenty dollars per gram* was used to determine fuel investment cost: a four percent annual inventory charge was used to calculate the total inventory charges per year.

9.4.2.3.2 Burn Up

The burn up of uranium in grams per year was calculated using the heat power of the reactor, and the equivalence: 1 MW (heat) = 1.18 gms uranium per day burned up. The burnup charges were computed using a value of twenty dollars per gram of enriched uranium*.

9.4.2.3.3 Reprocessing and Fabrication

A cylindrical reactor configuration was used to determine the maximum

*L. R. Hafstad, Atomic Power and Private Enterprise, p. 139, G.P.O., December, 1952. Printed for the use of the Joint Committee on Atomic Energy.

number of fuel elements which could be loaded into a reactor of specified radius. The loading per element was then obtained using 125% of critical loading required. Assuming an average value of burnup, the number of fuel elements reprocessed and refabricated annually was then obtained.

9.4.2.3.4 Total Fuel Charges

The total fuel charges are the sum of fabrication, reprocessing, burnup, and inventory charges. For a reactor operating 109 hours of a 168 hour week, the fabrication, reprocessing, and burnup charges were scaled down by an "on time" factor $\frac{109}{168} = 0.649$.

For the reactors operating continuously, an "on time" plant factor of 0.80 was used. The total fuel charges increase for the continuous operation cases, due to increased burn up, fabrication, and reprocessing charges accompanying a longer period of reactor operation.

9.4.3 Power Credits and Debits:

Systems involving power generation show credits against total annual charges for the sale of generated power, while no-power cases are charged with the cost of power required for plant operation.

In estimating gross power output the turbo-generator plants were assigned a flat 25% thermal efficiency, regardless of size.

Power credits in the cases with power generation were assigned as follows:

Ten (10) percent of gross generation during irradiation operations is credited at 16 mills per KWH, a figure representative of industrial power costs in the Chicago area (1). The remaining ninety (90) percent of power generated

(1) Lt. Col. Belmont Evans, USQMC, Private Communication.

during meat plant operations is sold at six (6) mills per KWH, a price considered reasonable for day-time sale of firm power. During the hours that meat handling operations are at a standstill the reactor and power plant operate for one-half the time. Here 95% of the generation is sold at only two mills, approximately the cost of conventional fuel, the low price reflecting low power demand.

The sum of credits so calculated is deducted from total annual charges.

Plants without a generating facility are charged with 5% of theoretical gross power calculated at 25% thermal efficiency.

9.5 Tabulations of Cost Estimates

Results of the cost estimates are shown for the POWER cases in Tables 9-I, 9-II, 9-III and 9-IV and for the No-POWER cases on Tables 9-V, 9-VI, 9-VII and 9-VIII.

The basic cases are those set up for one-hundred (100) minutes irradiation time with meat processing activities being conducted fifty (50) hours per week, equivalent to 260 annual working days. In order to maintain activity level the reactor is run for one-half of the remaining 118 hours of the week, or 59 hours. Total reactor operating time is then 109 hours out of 168 hours weekly. The equivalent plant factor is 0.649.

Systems operating under these conditions are No-POWER cases 10, 11, 42, 43 and 44 and POWER cases 10, 11, 37, 38, 35, 39, 36, 40, 41.

The effect of variations from the basic conditions described above are shown in POWER cases 35a and 35b, and in No-POWER cases 42a, 42b, and 42c.

9.6 Results of the Estimate

9.6.1 Best Basic Cases

Of the cases set up for 100 minutes irradiation time and a 109 hour week, the No-POWER system with lowest irradiation cost is case 42, at 3.1 cents per pound. The best POWER case in this category is case 36, at 5.0 cents per pound. The cost for case 35 (to be compared with that for continuous processing) is 5.7 cents per pound.

9.6.2 POWER vs. No-POWER

POWER generation cases 10, 11, and 35 result in almost identical irradiation costs as No-POWER cases 10, 11 and 43, which are of the same reactor heat power rating as the POWER systems. The edge favors the No-POWER cases slightly, since the increased charges on power plant investment and reactor system pressure rating more than offset the gain due to power sale credits.

It is concluded that the economy of this irradiation facility is not improved by the inclusion of a turbo-generator plant with the conditions and plant factor (0.649) described above.

9.6.3 Irradiation Time

For a given concentration of activated element in the blanket or core solution, the reactor power density required to achieve the specified irradiation dose varies inversely with irradiation time. As explained above, the basic cases were calculated for 100 minutes, an arbitrary maximum selected after consideration of the physical size of the facility, equipment capacity, etc., which increase in size with time in process. The 100 minute time then provides minimum power density and minimum reactor power rating for a given size of core. Case 42c, a variation of case 42, shows the effect of taking the power density to 280 KW per liter. Power required jumps from 17 MW to

to 23 MW and irradiation time drops to 55 minutes. Unit cost of irradiation increases from 3.1 cents (case 42) to 3.5 cents.

9.6.4 Continuous Processing

Any change in plant operating time directly affects annual fuel charges, operating costs, and power credits or debits. Until now only a 50 hour per week meat processing schedule has been discussed. Now the processing schedule is changed to observe the effect on plant economy.

The plant is now to be operated on a 24 hour basis, with a plant factor of 0.8. This is equivalent to meat irradiation for 134 hours of the week, or 292 days per year. During the remaining time the reactor is shut down. Irradiation time remains 100 minutes.

Upon this basic change several further variations are imposed. Cases 42a and 35a show the additional effect of allowing the daily meat throughput to increase with increased processing time, at the same hourly rate and reactor power as the base cases:

Former daily avg. rate = $5/7 \times 80,000 = 57,200$ lbs. per day

New daily avg. rate = $80,000 \times 24/10 \times 0.8 = 153,600$ lbs. per day

Throughput increase factor = $153,600/57,200 = 2.68$

The net effect of these changes is a reduction in processing costs for cases 42a and 35a to 1.3 cents and 2.2 cents, respectively, from those reported earlier for basic cases 42 and 35. These new costs represent about a 60% decrease. Although increased fuel cost causes annual charges to rise, the increased output of irradiated meat has the net effect of decreasing unit cost.

Another variation is illustrated by cases 42b and 35b. These cases also

operate on a 24 hour basis, but with daily output held constant, i. e., at reduced hourly throughput rates. In view of the reduced rate, the reactor size and power were also reduced, and the capital costs reduced from cases 42a and 35a in the ratio of the 0.6 power of the throughput ratio. Power density is maintained to keep activity at operating level.

Cases 42b and 35b show a reduction in production costs to 1.6 and 2.9 cents respectively. These are reductions of approximately 50% over corresponding cases 42 and 35.

The results of these cases underline the important effect of increased production together with high plant utilization. As shown here, this combination may cut processing cost by as much as 60%. Reduction of reactor power, with production unchanged, has an important but smaller effect.

9.6.5 Cladding of Fuel Elements

Cases 39, 40, 41 (power) have zirconium clad elements. Costs of irradiation are 27 cents, 59 cents, and 105 cents respectively. This high cost is due mainly to prohibitive zirconium fuel element fabrication and processing charges.

9.7.0 Summary

Economic trends favor a low pressure, no power system. This type system shows savings in investment, in fuel costs (due to use of aluminum clad and lower power), and in operating and maintenance charges.

Production schedules should be aimed at high plant utilization and high output consistent with fuel loading schedules and required downtime for maintenance.

Considering the effect on reactor power, advantage should be taken of

increasing irradiation time. This can be optimized by balancing cost of reactor systems against costs of the irradiation facility.

An activated element should be chosen which has a combination of high cross section and high decay strength. Here, indium is the better of the two selected. A more extensive investigation than was possible on this project might uncover other elements of equal worth.

Case 42 best meets these requirements and does so at lowest net irradiation cost, both for the basic case of intermittent operation and for the case of continuous operation.

TABLE 9-I
MATERIAL AND LABOR CHARGES
Cases With Power Generation

Case No.	Mn- "Dirty Core"		In - "Clean Core"				In- "Clean Core"			Cont. Process	
	10	11	37	38	35	36	39	40	41	35a	35b
Heat Power, Mw	114	120	93	64	39	31	23	55	112	39	15
REACTOR											
Pressure Vessel	239,500	239,500	183,600	183,600	100,300	100,300	117,100	186,600	301,000	100,300	--
Thermal Shield	10,400	10,400	6,600	6,600	4,360	4,360	4,360	8,200	12,000	4,360	--
Fuel Assy.	215,000	215,000	152,000	152,000	63,000	63,000	917,000	2,210,000	4,150,000	63,000	--
Biological Shield	68,000	68,000	58,200	58,200	41,200	41,200	41,200	56,200	78,000	41,200	--
Control System	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	--
PRIMARY COOLANT LOOP											
Pressurizer System	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	--
Ht. Exch. / Steam Drum	570,000	600,000	465,000	320,000	195,000	155,000	115,000	275,000	560,000	195,000	--
Dump Tank	15,000	15,000	13,000	10,000	8,000	8,000	7,000	8,000	15,000	8,000	--
Pipe and Valves	250,000	252,000	194,000	145,000	79,000	58,000	58,000	105,000	250,000	79,000	--
Pumps and Motors	250,000	250,000	224,000	196,000	160,000	140,000	123,000	182,000	252,000	160,000	--
Steam Power Plant	3,140,000	3,300,000	2,560,000	1,760,000	1,074,000	854,000	633,000	1,515,000	3,080,000	1,074,000	--
BLANKET LOOP											
Pipe and Valves	7,600	7,600	7,600	5,000	5,000	3,600	3,600	5,000	5,300	5,000	--
Pumps and Motors	64,000	64,000	59,000	34,000	28,000	25,000	22,000	34,000	64,000	28,000	--
Flash Cooler	-	-	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	--
Surface Cond. or Heat Exch.	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	--
Soln. Make-up Equip.	-	-	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	--
Dump Tank	7,200	7,200	7,200	7,200	7,200	7,200	7,200	7,200	7,200	7,200	--
PROCESS INSTRUMENTATION	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	--
SHIELD COOLING SYSTEM	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	--
EMERGENCY COOLING TANK	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	--
ACTIVATED SOLN. CHEMICALS	-	-	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	--

**TABLE 9-I(Cont.)
MATERIAL AND LABOR CHARGES
Cases With Power Generation**

Case No. Heat Power, MW.	Mo- "Dirty Core"		In- "Clean Core"				In- "Clean Core"			Cont. Process	
	10 114	11 120	37 93	38 64	35 39	36 31	39 23	40 55	41 112	35a 39	35b 15
STACK	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	--
HOT CELLS	450,000	450,000	450,000	450,000	450,000	450,000	450,000	450,000	450,000	450,000	--
CORE HANDLING EQUIP.	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	--
CRANE	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	--
IRR. FACILITY	163,000	163,000	163,000	163,000	163,000	163,000	163,000	163,000	163,000	163,000	--
BLDG. AND SITE LEVEL.*	1,050,000	1,100,000	965,000	870,000	695,000	655,000	615,000	775,000	1,060,000	695,000	--
SUB TOTAL	6,919,700	7,161,700	5,945,200	4,797,600	3,510,060	3,164,660	3,713,460	6,419,200	10,884,500	3,510,000	--
10% CONTINGENCIES	691,970	716,170	594,520	479,760	351,006	316,466	371,346	641,920	1,088,450	351,006	--
10% ENGINEERING	691,970	716,170	594,520	479,760	351,006	316,466	371,346	641,920	1,088,450	351,006	--
10% CONTRACTOR	691,970	716,170	594,520	479,760	351,006	316,466	371,346	641,920	1,088,450	351,006	--
TOTAL - LAND ONLY	250,000	250,000	250,000	250,000	250,000	250,000	250,000	250,000	250,000	250,000	--
ERECTED COST*	8,745,610	9,060,210	7,478,760	5,986,880	4,313,078	3,864,050	4,577,498	8,094,960	13,899,850	4,313,078	2,270,000

Notes: (1) Capital investment charges for Case 35a were assumed to be the same as for Case 35.
(2) Capital investment charges for Case 35b were obtained by scale down of capital investment for Case 35.
Apply 0.6 rule to throughput ratio.

* Erected cost includes all costs above except land which is arbitrarily charged at \$250,000;
To obtain erected cost deduct land cost from Bldg. and Site cost before totaling figures.

TABLE q-II

FUEL CHARGES - CASES WITH POWER GENERATION

Case No. Heat Power, (MW)	<u>Mn - Dirty Core</u>		<u>Indium - Clean Core</u>				<u>Indium - Clean Core</u>			<u>Contin. Process</u>	
	10 114	11 120	37 93	38 64	35 39	36 31	39 23	40 55	41 112	35a 39	35b 15
Critical Mass (Kg)	75.5	88.8	26.5	26.5	9.50	9.40	4.30	10.70	22.8	9.50	--
Excess Mass (B.U. Xe)(Kg)	18.7	22.2	6.7	6.7	1.68	2.40	1.08	2.70	5.7	2.48	--
Total Loading, (Kg)	94.2	111.0	33.2	33.2	11.18	11.80	5.38	13.40	28.5	11.98	--
Fuel Cost (\$20 per Gram) ⁽¹⁾	1,890,000	2,218,000	664,000	664,000	240,000	236,500	107,800	268,000	571,500	240,000	--
Annual Fuel Inventory Chg.	75,700	84,700	26,500	26,500	9,600	9,440	4,280	10,720	22,850	9,600	--
Annual Burn Up (Kg) ⁽¹⁾	49.0	51.7	40.2	27.6	16.8	13.35	9.9	23.6	49.0	16.8	--
Annual B. U. Chg. (\$20/gm)	981,000	1,035,000	805,000	552,000	336,000	267,000	198,000	472,000	980,000	336,000	--
Annual Reproc. Chg.	491,000	517,000	398,000	275,000	168,000	133,000	100,000	237,000	483,000	168,000	--
Annual Fabr. Chg.	466,000	415,000	790,000	544,000	372,000	295,000	7,100,000	16,350,000	29,300,000	372,000	--
Total Annual Fuel Chg.	2,014,000	2,052,000	2,029,000	1,398,000	886,000	704,000	7,402,000	17,070,000	30,786,000	886,000	--
Total Adjusted Fuel Chgs.*	1,336,000	1,362,000	1,327,000	917,000	575,000	459,000	4,794,000	11,091,000	20,003,000	701,000	261,000**

* Adjusted Fuel Chgs. for intermittent cases obtained by multiplying total annual fuel chgs. by ratio 109/168, i.e. by ratio of weekly operating hours to total weekly hours; for 35a and 35b multiply by 0.80.

** Charges for case 35b obtained by linear scale-down from case 35a. (use throughput ratio = 2.68)
 (1) L. R. Hafstad, "Atomic Power and Private Enterprise", p. 139, Dec., 1952, G.P.O. Printed for use of Joint Committee on Atomic Energy.

TABLE 9-IV

ANNUAL CHARGES

Cases With Power Generation

CASE	<u>Mn - "Dirty Core"</u>			<u>In - "Clean Core"</u>			<u>In - "Clean Core"</u>			<u>Continuous Process</u>	
	10	11	37	38	35	36	39	40	41	35a	35b
Ht. Power, MW	114	120	93	64	39	31	23	55	112	39	15
Total Capital Cost, \$(Depr. Items)	8,746,000	9,060,000	7,479,000	5,987,000	4,313,000	3,864,000	4,577,000	8,095,000	13,900,000	4,313,000	2,270,000
Total Capital Cost Land	250,000	250,000	250,000	250,000	250,000	250,000	250,000	250,000	250,000	250,000	250,000
Annual Charges:											
Fixed Charges, Land(12%)	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000
Fixed Charges (15% Depr. Items)	1,310,000	1,360,000	1,120,000	899,000	646,000	580,000	686,000	1,210,000	2,080,000	646,000	341,000
Fuel Charges	1,336,000	1,362,000	1,327,000	917,000	575,000	459,000	4,794,000	11,091,000	20,003,000	701,000	261,000
Op. and Maintenance (25% F.C.)	335,000	348,000	288,000	232,000	169,000	153,000	179,000	310,000	527,000	169,000	94,600
Total Annual Debits, \$	3,011,000	3,100,000	2,765,000	2,078,000	1,420,000	1,222,000	5,689,000	12,641,000	22,640,000	1,546,000	726,600
Annual Power Credits, \$	683,000	720,000	557,000	384,000	233,000	186,000	138,000	331,000	671,000	328,300	126,500
Net Annual Cost of Operation, \$	2,328,000	2,380,000	2,208,000	1,694,000	1,187,000	1,036,000	5,551,000	12,310,000	21,969,000	1,217,700	600,100
Net Cost per Pound of Meat, Cents	11.2	11.4	10.6	8.1	5.7	5.0	26.6	59.0	105.0	2.18	2.88

TABLE 9-III

POWER CREDITS

Cases With Power Generation

CASE NO.	Mn - "Dirty Core"			In - "Clean Core"			In - "Clean Core"			Cont. Process	
	10	11	37	38	35	36	39	40	41	35a	35b
Reactor Heat Power, MW	114	120	93	64	39	31	23	55	112	39	15
Gross Thermal Eff.	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Power Plant Gross Cap. KW	28,500	30,000	23,200	16,000	9,750	7,750	5,750	13,800	28,000	9,750	3,750
Hours, Per Wk.											
Power used in plant aux.	50	50	50	50	50	50	50	50	50	135	135
Power sold for other manu.	50	50	50	50	50	50	50	50	50	50	50
Power sold during other hrs.	59	59	59	59	59	59	59	59	59	85	85
Power Credits, mills/KWH											
Plant Aux. 10% of Power	16	16	16	16	16	16	16	16	16	16	16
Other Manufacturing 90% of Power	6	6	6	6	6	6	6	6	6	6	6
Other hrs. only 90% of Gen.	2	2	2	2	2	2	2	2	2	2	2
Annual Credits Allotted to Plant Aux.	\$118,000	\$125,000	\$ 96,580	\$ 66,500	\$ 40,500	\$ 32,200	\$23,900	\$ 57,400	\$116,000	\$109,400	\$ 42,400
Annual Credits Allotted to Mfg. Period Sales	399,000	420,000	325,000	224,000	136,000	109,000	80,500	193,000	392,000	137,000	52,600
Annual Credits Allotted to Off Time	<u>166,000</u>	<u>175,000</u>	<u>135,000</u>	<u>93,200</u>	<u>56,800</u>	<u>45,100</u>	<u>33,500</u>	<u>80,500</u>	<u>163,000</u>	<u>81,900</u>	<u>31,500</u>
Total Annual Power Credits	\$683,000	\$720,000	\$556,500	\$383,700	\$233,300	\$186,300	\$137,900	\$330,900	\$671,000	\$328,300	\$126,500

TABLE 9-V
MATERIAL AND LABOR COSTS
Cases without Power Generation

Case Number Ht. Power, MW	<u>Mn-"Dirty Core"</u>		<u>In-"Clean Core"</u>			<u>Special</u>		
	10 114	12 120	42 17	43 39	44 80	42a 17	42b 6	42c 23c
<u>REACTOR</u>								
Pressure Vessel (1)	54,500	53,500	26,000	41,900	58,700	26,600	---	26,600
Thermal Shield (1)	12,000	12,000	4,360	8,200	12,000	4,360	---	4,360
Fuel Assay (1)	215,000	215,000	22,000	57,500	107,800	22,000	---	22,000
Biological Shield (1)	68,000	68,000	41,200	58,200	78,000	41,200	---	41,200
Control System (1)	50,000	50,000	50,000	50,000	50,000	50,200	---	50,200
<u>PRIMARY COOLANT LOOP</u>								
Pipe and Valves	150,000	150,000	20,000	48,000	87,000	20,000	---	20,000
Pump and Motors (2)	250,000	250,000	106,000	155,000	210,000	106,000	---	106,000
Flash and Cooler (1)	23,000	25,000	9,000	12,000	16,000	9,000	---	9,000
Surface Condenser (1)	924,000	966,000	140,000	315,000	645,000	140,000	---	140,000
Dump Tank (1)	15,000	15,000	5,000	8,000	13,000	5,000	---	5,000
Solution Make-Up Equip.	10,000	10,000	Included	in Process	Water Equipment	---	---	see "a"
<u>BLANKET LOOP</u>								
Pipe and Valves	7,600	7,600	4,000	5,000	7,000	4,000	---	4,000
Pump and Motors (2)	45,000	45,000	25,000	28,000	38,000	25,000	---	25,000
Flash Cooler (1)	2,000	2,000	2,000	2,000	2,000	2,000	---	2,000
Surface Condenser (1)	15,000	15,000	15,000	15,000	15,000	15,000	---	15,000
Solution Make-Up Equip.	---	---	5,000	5,000	5,000	---	---	5,000
<u>PROCESS INSTRUMENTATION</u>	100,000	100,000	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	25,000	---	25,000
<u>EMERGENCY COOLING TANK SYSTEM</u>	20,000	20,000	20,000	20,000	20,000	20,000	---	20,000
<u>WATER PURIFICATION SYSTEM</u>	50,000	50,000	50,000	50,000	50,000	50,000	---	50,000

TABLE 9-V (continued)
MATERIAL AND LABOR COSTS
Cases without Power Generation

Case Number Ht. Power, MW	<u>Mn-"Dirty Core"</u>		<u>In-"Clean Core"</u>			<u>Cont. Process</u>		<u>Decreased Irr. Time</u>
	10 114	11 120	42 17	43 39	80 44	42a 17	42b 6b*	42c 23c
<u>INDIUM SOLN.</u>	---	---	10,000	10,000	10,000	10,000	---	10,000
<u>STACK</u>	10,000	10,000	10,000	10,000	10,000	10,000	---	10,000
<u>HOT CELLS</u>	350,000	350,000	350,000	350,000	350,000	350,000	---	350,000
<u>COPE HANDLING</u>	20,000	20,000	20,000	20,000	20,000	20,000	---	20,000
<u>CRANE</u>	100,000	100,000	100,000	100,000	100,000	100,000	---	100,000
<u>IRRADIATION FACILITY</u>	163,000	163,000	163,000	163,000	163,000	163,000	---	135,000
<u>BUILDING and SITE DEV.</u>	1,050,000	1,100,000	585,000	695,000	900,000	585,000	---	585,000
<u>SUB-TOTAL-INSTLD. MAT.</u>	3,729,100	3,822,100	1,768,160	2,241,800	3,091,700	1,768,000	---	1,740,160
<u>10% CONTINGENCIES</u>	372,910	382,210	176,816	224,180	309,170	176,800	---	174,000
<u>10% ENGINEERING</u>	372,910	382,210	176,816	224,180	309,170	176,800	---	174,000
<u>10% CONTRACTOR</u>	372,910	382,210	176,816	224,180	309,170	176,800	---	174,000
TOTAL COST	4,847,830	4,968,400	2,298,608	2,914,340	4,019,210	2,298,600	1,270,000	2,262,200
LAND	- 250,000	- 250,000	- 250,000	- 250,000	- 250,000	- 250,000	- 250,000	- 250,000
	4,597,830	4,718,400	2,048,608	2,664,340	3,769,210	2,048,600	1,020,000	2,012,200

* Capital investments for case 42b obtained by scale down from case 42a.

TABLE 9-VI

FUEL CHARGES - CASES WITHOUT POWER GENERATION

<u>Case No.</u>	<u>Mn-Dirty Core</u>		<u>In-Clean Core</u>			<u>Cont. Process</u>		<u>Decreased Irr. Time</u>
	(10)	(11)	(42)	(43)	(44)	(42a)	(42b)	(42c)
Heat Power (MW)	114	120	17	39	80	17	11	23
Critical Mass (KG)	75.5	88.8	5.50	11.9	24.0	5.50	-	5.50
Excess Mass (Bu & Xe)	18.9	22.2	1.38	2.0	7.0	1.38	-	1.38
Total Loading (KG)	94.4	111.0	6.88	13.9	31.0	6.88	-	6.88
Fuel Cost (\$20./gram)	1,890,000	2,218,000	133,500	278,000	619,000	133,500	-	133,500
Annual Fuel Inventory Chg.	75,700	84,700	5,300	11,120	24,800	5,300	-	5,300
Annual Fuel Burn Up (KG)	49.0	51.7	7.04	16.75	34.7	7.04	-	9.9
Annual BU Chg. (\$20./gm)	981,000	1,035,000	140,700	335,000	694,000	140,700	-	198,000
Annual Reproc. Chg.	491,000	517,000	73,500	168,600	343,500	73,500	-	99,300
Annual Fabr. Chg.	466,000	415,000	105,600	271,000	515,000	23,800	-	146,500
Total Annual Fuel Chg. (Based on 365 days)	2,014,000	2,052,000	325,000	786,000	1,577,000	325,000	-	447,000
Total Adjusted Fuel Chg.*	1,334,000	1,361,000	212,000	514,000	1,010,000	260,000	96,700**	293,000

* Refer to same note table 9-II; use 0.80 factor for cases 42a and 42b.

** Fuel charge for case 42b obtained by linear scale down from case 42a.

TABLE 9-VII

OPERATING POWER DEBITS
CASES WITHOUT POWER GENERATION

	<u>Mn-"Dirty Core"</u>		<u>In-"Clean Core"</u>			<u>Cont. Process</u>		<u>Decreased Irr. Time</u>
Case No.	(10)	(11)	(42)	(43)	(44)	(42a)	(42b)	(42c)
Heat Power, MW	114	120	17	39	80	17	6	23
Gross Thermal Eff.	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Power Plant Gross Cap., KW	28,500	30,000	4,260	9,750	20,000	4,260	1,500	5,750
Operating Time								
Processing Time (Hrs. per wk.)	50	50	50	50	50	135	135	50
Total Reactor Operating Time, Incl. Proc. (Hrs. per week)	109	109	109	109	109	135	135	109
Power Debits								
Power Charge (100% total op. time) (mils/KWH)	16	16	16	16	16	16	16	16
Total Annual Power Debits (5% Gross Cap.) (\$/yr.)	129,000	136,000	19,300	44,300	90,800	23,800	8,410	26,100

TABLE 9-VIII

ANNUAL CHARGES

CASES WITHOUT POWER GENERATION

Case No.	<u>Mn- "Dirty Core"</u>		(42)	<u>In- "Clean Core"</u>		<u>Cont. Process</u>		<u>Decreased</u>
	(10)	(11)		(43)	(44)	(42a)	(42b)	<u>Irr. Time</u>
								(42c)
Heat Power, MW	114	120	17	39	80	17	6	23
Total Capital Cost \$ (Depr. Items)	4,597,830	4,718,400	2,048,600	2,644,340	4,769,210	2,048,000	1,020,000	2,012,000
Total Capital Cost Land	250,000	250,000	250,000	250,000	250,000	250,000	250,000	250,000
Annual Charges								
Fixed Charges Land (12%)	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000
Fixed Charges (15% Depr. Items)	688,000	707,000	308,000	397,000	716,000	308,000	153,000	303,000
Fuel Charges	1,334,000	1,361,000	212,300	513,600	1,010,000	260,300	96,700	293,000
Op. & Maintenance (25% F.C.)	179,900	184,300	84,500	107,000	186,500	84,500	45,700	75,700
Annual Power Charge (\$, 5% of Theoretical Gross Power @ 16 mils/KWHR	129,000	136,000	19,300	44,300	90,800	23,800	8,400	26,100
Net Annual Cost of Operation(\$)	2,360,900	2,418,300	654,100	1,091,900	2,033,300	706,600	333,810	727,800
Net Cost Per Pound of Meat, Cents/Lb.	11.3	11.6	3.14	5.25	9.75	1.26	1.60	3.48

APPENDIX A: EDGE EFFECTS IN SLAB SOURCE IRRADIATION

The problem is to find the overlap of the source plane over the sides of the conveyor system needed to keep the dose variation within the required limits.

Edge

The dose at the centerline of the conveyor belt is given as:

$$(1) \quad D_c \sim \int_{\text{Area}} \frac{\sigma_0 dx dy}{4\pi R^2} G(E, R)$$

from figure $R^2 = x^2 + z^2$ and $G(E, R) = e^{-uR} B(R) \approx 1(\text{in air})$

such that

$$D_c \sim \int \frac{\sigma_0 dx dy}{4\pi(x^2 + z^2)}$$

since the variation in dose is independent of the y direction eq (1) becomes:

$$(2) \quad D_c \sim \frac{\sigma_0}{4\pi} \int_{-1'}^{+1'} \frac{dx}{x^2 + z^2}$$

Now, likewise for the dose at the edge of the conveyor system:

$$(3) \quad D_{\text{Edge}} \sim \int \frac{\sigma_0 dx dy}{4\pi R'^2} G(E, R')$$

but $R'^2 = (1+x)^2 + z^2$ and $G \approx 1$

such that

$$D_{\text{Edge}} \sim \frac{\sigma_0}{4\pi} \int \frac{dx}{(1+x)^2 + z^2}$$

Now, let $q = 1 + x$

$dq = dx$

$$(4) \quad D_E \sim \frac{\sigma_0}{4\pi} \int_{1-1'}^{1+1'} \frac{dq}{q^2 + z^2}$$

To keep the dose within specified limits

$$(5) \quad D = K D_E \quad K = 1 + \text{dose variation}$$

$$\int_{-1'}^{1'} \frac{dx}{x^2 + z^2} = K \int_{1-1'}^{1+1'} \frac{dq}{q^2 + z^2}$$

but,
$$\int_{-1'}^1 \frac{dx}{x^2 + z^2} = \frac{2}{z} \tan^{-1} \frac{1}{z}$$

and
$$\int_{1-1'}^{1+1'} \frac{dq}{q^2 + z^2} = \frac{1}{z} \left\{ \tan^{-1} \left(\frac{1+1'}{z} \right) + \tan^{-1} \left(\frac{1'-1}{z} \right) \right\}$$

substituting into Equation 5, one has

$$(6) \quad \tan^{-1} \frac{1'}{z} = \frac{K}{2} \left\{ \tan^{-1} \frac{1'+1}{z} + \tan^{-1} \frac{1'-1}{z} \right\}$$

APPENDIX B: INDUCED ACTIVITY IN BEEF

The permissible thermal neutron flux to keep the induced activity below a measurable level may be calculated as follows:

$$\text{Production rate of active atoms} = \phi_{th} \Sigma_a$$

$$\text{Decay rate of active atoms} = \lambda N_a$$

where ϕ = thermal neutron flux

Σ_a = macroscopic absorption cross-section of the element

λ = decay constant

N_a = number of active atoms per unit volume

The maximum saturated activity occurs when the decay rate becomes equal to the production rate in which case $N_a^{max} = \frac{\phi \Sigma_a}{\lambda}$, at any time during build-up of activity: $N_a = \frac{\phi \Sigma_a}{\lambda} (1 - e^{-\lambda t})$ Eq. (1)

For a finite exposure time, t_e , but a longer decay time N_a is given by the following:

$$N_a = \frac{\phi \Sigma_a}{\lambda} (1 - e^{-\lambda t_e}) e^{-\lambda(t - t_e)} \quad \text{Eq. (2)}$$

rearranging Equation (2) becomes:

$$N_a = \frac{\phi \Sigma_a}{\lambda} (e^{\lambda t_e} - 1) e^{-\lambda t} \quad \text{Eq. (3)}$$

differentiating,

$$\frac{dN_a}{dt} = \frac{\phi \Sigma_a}{\lambda} (e^{\lambda t_e} - 1) e^{-\lambda t} (-\lambda) \quad \text{Eq. (4)}$$

solving for ϕ , one has

$$\phi = \left(\frac{\frac{dN_a}{dt}}{\Sigma_a} \right) \left(\frac{e^{\lambda t}}{e^{\lambda t_e} - 1} \right) \quad \text{Eq. (5)}$$

In general for a number of elements to be activated, Equation 5 becomes:

$$\phi = \frac{\left(-\frac{dN_a}{dt} \right)}{\left[\sum a_1 e^{-\lambda_1 t} (e^{\lambda_1 t_e} - 1) \right] + \left[\sum a_2 e^{-\lambda_2 t} (e^{\lambda_2 t_e} - 1) \right] + \dots} \quad \text{Eq. (6)}$$

The measurable activity, $\left(-\frac{dN_a}{dt} \right)$, is assumed to be on the average 0.01 decay/cm³ - sec.

The following table indicate the composition of beef and the appropriate constants.

TABLE I

The following table contains elements and their abundances found in beef as given by the American Scientist 40, 404 (1952) and isotopes, cross sections, etc., obtained from AECU-2040 and other documents.

Element	Isotope	gm/c.c.	$\Sigma a, \text{cm}^{-1}$	λ, sec^{-1}	$\Sigma a \lambda, \text{cm}^{-1} \text{sec}^{-1}$	rating
Al	27	1×10^{-7}	5.06×10^{-10}	5.01×10^{-3}	2.5×10^{-12}	
Ca	48	4.5×10^{-8}	6.43×10^{-10}	1.36×10^{-3}	8.8×10^{-13}	
Cr	50	1.32×10^{-9}	2.62×10^{-10}	4.44×10^{-7}	11.6×10^{-17}	
Co	59	2×10^{-8}	$71.7 \times 10^{-10}/2$	1.08×10^{-3}	35.0×10^{-13}	
Cu	63	29.7×10^{-7}	12.64×10^{-10}	1.49×10^{-5}	18.8×10^{-13}	5
	65	13.3×10^{-7}	2.67×10^{-10}	2.68×10^{-3}	7.15×10^{-11}	
F						
Fe	58	101×10^{-8}	86.6×10^{-10}	1.70×10^{-7}	1.48×10^{-15}	
Pb	208	5.2×10^{-8}	$.000702 \times 10^{-10}$	3.3 hrs.	-----	
Mn	55	20×10^{-8}	2.85×10^{-10}	7.4×10^{-5}	2.1×10^{-12}	10
Mg	26	$22,600 \times 10^{-8}$	2.710×10^{-10}	1.21×10^{-3}	3.26×10^{-10}	4
Mo	98	3.33×10^{-8}	0.276×10^{-10}	67 hours	-----	
	100	1.33×10^{-8}	0.186×10^{-10}	7.7×10^{-4}	1.43×10^{-14}	
Ni	64	0.03×10^{-8}	0.086×10^{-10}	2.6 hours	-----	
P	31	$1,600,000 \times 10^{-8}$	$644,000 \times 10^{-10}$	5.6×10^{-7}	3.60×10^{-11}	7
Si	30	1.85×10^{-8}	1.54×10^{-10}	2.7 hours	-----	
K	41	$324,000 \times 10^{-8}$	$592,000 \times 10^{-10}$	1.52×10^{-5}	9.0×10^{-10}	2
Ag	107	6.64×10^{-8}	116×10^{-10}	5×10^{-3} 2.3m	5.8×10^{-11}	6
	109	6.33×10^{-8}	30.4×10^{-10}	0.28, 24sec.	8.5×10^{-9}	1
Na	23	$400,000 \times 10^{-8}$	$542,000 \times 10^{-10}$	1.28×10^{-5}	6.9×10^{-10}	3
Sn	112	0.019×10^{-8}	0.0138×10^{-10}	30 m.	-----	
	120	0.67×10^{-8}	0.0109×10^{-10}	---	---	
Zn	64	$22,000 \times 10^{-8}$	$10,700 \times 10^{-10}$	4.6×10^{-8}	4.95×10^{-4}	8
	68	$8,370 \times 10^{-8}$	690×10^{-10}	2.22×10^{-4}	1.52×10^{-11}	
	70	284×10^{-8}	23×10^{-10}	5.25×10^{-3}	1.21×10^{-11}	

TABLE II

(The ten dominating activities selected from Table I)

Isotope	$\sum a \lambda_{cm-1} sec^{-1}$	$\sum a (e^{\lambda t_0} - 1)$	$e^{-\lambda t}$	$\sum a (e^{\lambda t_0} - 1) (e^{-\lambda t})$
Ag-109	8.5×10^{-9}	5.1×10^{-6}	-503	0
K-41	9.0×10^{-10}	5.4×10^{-7}	0.973	5.22×10^{-7}
Na-23	6.9×10^{-10}	4.1×10^{-7}	0.977	4.0×10^{-7}
Mg-26	3.3×10^{-10}	(2.0×10^{-7}) $\frac{1.08}{0.73} = 2.97 \times 10^{-7}$	0.113	3.35×10^{-8}
Cu-65	7.2×10^{-11}	4.3×10^{-8}	0.008	
Ag-107	5.8×10^{-11}	3.5×10^{-8}	0.0001	
P-31	3.6×10^{-11}	2.2×10^{-8}	0.999	2.2×10^{-8}
Zn-68	1.5×10^{-11}	9.0×10^{-9}	.40	
Zn-70	1.2×10^{-11}	7.2×10^{-9}	0.0001	
Mn-55	2.1×10^{-12}	(1.2×10^{-9})	0.875	$\frac{1.05 \times 10^{-9}}{9.8 \times 10^{-7}}$

Using these results in equation (6) with $\left(-\frac{dNa}{dt}\right) = 10^{-2}$, one has

$$\phi = \frac{10^{-2}}{9.8 \times 10^{-7}} = 1.02 \times 10^4 \frac{\text{Neut.}}{\text{cm.}^2 \text{ sec.}}$$

as the maximum allowable level for the flux.

APPENDIX C

TABULATED DATA FOR TWO-GROUP, TWO-REGION ORACLE CALCULATIONS

TABLE A

"DIRTY CORE" REACTORS - MANGANESE SULFATE ACTIVATED IN CORE
 TWO GROUP - TWO REGION CALCULATIONS BY ORACLE
 STAINLESS STEEL CLAD ELEMENTS
 560°F CORE TEMPERATURE

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
90	90	90	90	90	90	90	90	90	70	70	70	50	50	50	50	50	50	50
0.10	0.10	0.10	0.20	0.20	0.20	0.50	0.50	0.50	0.10	0.20	0.50	0.10	0.10	0.20	0.20	0.50	0.50	0.50
0.01	0.10	0.50	0.01	0.10	0.50	0.01	0.10	0.50	0.05	0.05	0.05	0.01	0.50	0.01	0.50	0.01	0.50	0.50
0.609 X 10 ⁻²	0.232 X 10 ⁻²	0.216 X 10 ⁻²	0.442 X 10 ⁻²	0.216 X 10 ⁻²	0.660 X 10 ⁻³	0.914 X 10 ⁻²	0.688 X 10 ⁻²	0.323 X 10 ⁻²	0.440 X 10 ⁻²	0.375 X 10 ⁻²	0.978 X 10 ⁻²	0.981 X 10 ⁻²	0.101 X 10 ⁻²	0.714 X 10 ⁻²	0.107 X 10 ⁻²	0.141 X 10 ⁻¹	0.107 X 10 ⁻¹	0.486 X 10 ⁻²
0.552 X 10 ⁻²	0.210 X 10 ⁻²	0.195 X 10 ⁻²	0.401 X 10 ⁻²	0.195 X 10 ⁻²	0.597 X 10 ⁻³	0.845 X 10 ⁻²	0.634 X 10 ⁻²	0.297 X 10 ⁻²	0.399 X 10 ⁻²	0.340 X 10 ⁻²	0.907 X 10 ⁻²	0.893 X 10 ⁻²	0.917 X 10 ⁻²	0.649 X 10 ⁻²	0.975 X 10 ⁻³	0.132 X 10 ⁻¹	0.995 X 10 ⁻²	0.454 X 10 ⁻²
0.399 X 10 ⁻²	0.152 X 10 ⁻²	0.141 X 10 ⁻²	0.290 X 10 ⁻²	0.141 X 10 ⁻²	0.430 X 10 ⁻³	0.655 X 10 ⁻²	0.488 X 10 ⁻²	0.227 X 10 ⁻²	0.290 X 10 ⁻²	0.247 X 10 ⁻²	0.711 X 10 ⁻²	0.656 X 10 ⁻²	0.699 X 10 ⁻³	0.478 X 10 ⁻²	0.711 X 10 ⁻³	0.107 X 10 ⁻¹	0.801 X 10 ⁻²	0.366 X 10 ⁻²
0.201 X 10 ⁻²	0.759 X 10 ⁻³	0.705 X 10 ⁻³	0.146 X 10 ⁻²	0.705 X 10 ⁻³	0.214 X 10 ⁻³	0.395 X 10 ⁻²	0.289 X 10 ⁻²	0.133 X 10 ⁻²	0.147 X 10 ⁻²	0.126 X 10 ⁻²	0.442 X 10 ⁻²	0.346 X 10 ⁻²	0.345 X 10 ⁻³	0.252 X 10 ⁻²	0.367 X 10 ⁻³	0.722 X 10 ⁻²	0.527 X 10 ⁻²	0.241 X 10 ⁻²
0.523 X 10 ⁻³	0.186 X 10 ⁻³	0.180 X 10 ⁻³	0.448 X 10 ⁻³	0.180 X 10 ⁻³	0.413 X 10 ⁻⁴	0.217 X 10 ⁻²	0.116 X 10 ⁻²	0.368 X 10 ⁻³	0.426 X 10 ⁻³	0.395 X 10 ⁻³	0.224 X 10 ⁻²	0.155 X 10 ⁻²	0.120 X 10 ⁻³	0.133 X 10 ⁻²	0.123 X 10 ⁻²	0.577 X 10 ⁻²	0.314 X 10 ⁻²	0.123 X 10 ⁻³
0.599 X 10 ⁻³	0.196 X 10 ⁻³	0.196 X 10 ⁻³	0.555 X 10 ⁻³	0.196 X 10 ⁻³	0.352 X 10 ⁻⁶	0.253 X 10 ⁻²	0.896 X 10 ⁻³	0.159 X 10 ⁻³	0.421 X 10 ⁻³	0.422 X 10 ⁻³	0.187 X 10 ⁻²	0.166 X 10 ⁻²	0.105 X 10 ⁻³	0.165 X 10 ⁻²	0.105 X 10 ⁻³	0.673 X 10 ⁻²	0.243 X 10 ⁻²	0.460 X 10 ⁻³
0.290 X 10 ⁻³	0.909 X 10 ⁻⁴	0.911 X 10 ⁻⁴	0.292 X 10 ⁻³	0.911 X 10 ⁻⁴	0.156 X 10 ⁻⁴	0.132 X 10 ⁻²	0.410 X 10 ⁻³	0.706 X 10 ⁻⁴	0.197 X 10 ⁻³	0.198 X 10 ⁻³	0.864 X 10 ⁻³	0.839 X 10 ⁻³	0.453 X 10 ⁻⁴	0.846 X 10 ⁻³	0.452 X 10 ⁻⁴	0.343 X 10 ⁻²	0.108 X 10 ⁻²	0.198 X 10 ⁻³
0.113 X 10 ⁻³	0.340 X 10 ⁻⁴	0.341 X 10 ⁻⁴	0.114 X 10 ⁻³	0.341 X 10 ⁻⁴	0.583 X 10 ⁻⁵	0.517 X 10 ⁻³	0.153 X 10 ⁻³	0.264 X 10 ⁻⁴	0.733 X 10 ⁻⁴	0.737 X 10 ⁻⁴	0.321 X 10 ⁻³	0.318 X 10 ⁻³	0.154 X 10 ⁻⁴	0.327 X 10 ⁻³	0.164 X 10 ⁻⁴	0.130 X 10 ⁻²	0.393 X 10 ⁻³	0.718 X 10 ⁻⁴
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.338 X 10 ⁻¹	0.340 X 10 ⁻¹	0.340 X 10 ⁻¹	0.338 X 10 ⁻¹	0.340 X 10 ⁻¹	0.340 X 10 ⁻¹	0.304 X 10 ⁻¹	0.308 X 10 ⁻¹	0.311 X 10 ⁻¹	0.433 X 10 ⁻¹	0.433 X 10 ⁻¹	0.382 X 10 ⁻¹	0.595 X 10 ⁻¹	0.602 X 10 ⁻¹	0.595 X 10 ⁻¹	0.602 X 10 ⁻¹	0.497 X 10 ⁻¹	0.508 X 10 ⁻¹	0.507 X 10 ⁻¹
0.307 X 10 ⁻¹	0.308 X 10 ⁻¹	0.308 X 10 ⁻¹	0.308 X 10 ⁻¹	0.308 X 10 ⁻¹	0.308 X 10 ⁻¹	0.281 X 10 ⁻¹	0.284 X 10 ⁻¹	0.286 X 10 ⁻¹	0.393 X 10 ⁻¹	0.393 X 10 ⁻¹	0.354 X 10 ⁻¹	0.542 X 10 ⁻¹	0.545 X 10 ⁻¹	0.542 X 10 ⁻¹	0.547 X 10 ⁻¹	0.466 X 10 ⁻¹	0.475 X 10 ⁻¹	0.474 X 10 ⁻¹
0.222 X 10 ⁻¹	0.222 X 10 ⁻¹	0.222 X 10 ⁻¹	0.222 X 10 ⁻¹	0.222 X 10 ⁻¹	0.222 X 10 ⁻¹	0.218 X 10 ⁻¹	0.218 X 10 ⁻¹	0.219 X 10 ⁻¹	0.285 X 10 ⁻¹	0.285 X 10 ⁻¹	0.278 X 10 ⁻¹	0.389 X 10 ⁻¹	0.399 X 10 ⁻¹	0.398 X 10 ⁻¹	0.399 X 10 ⁻¹	0.378 X 10 ⁻¹	0.388 X 10 ⁻¹	0.381 X 10 ⁻¹
0.112 X 10 ⁻¹	0.111 X 10 ⁻¹	0.111 X 10 ⁻¹	0.112 X 10 ⁻¹	0.111 X 10 ⁻¹	0.110 X 10 ⁻¹	0.131 X 10 ⁻¹	0.129 X 10 ⁻¹	0.128 X 10 ⁻¹	0.145 X 10 ⁻¹	0.145 X 10 ⁻¹	0.173 X 10 ⁻¹	0.210 X 10 ⁻¹	0.206 X 10 ⁻¹	0.210 X 10 ⁻¹	0.206 X 10 ⁻¹	0.255 X 10 ⁻¹	0.251 X 10 ⁻¹	0.252 X 10 ⁻¹
0.947 X 10 ⁻³	0.885 X 10 ⁻³	0.887 X 10 ⁻³	0.960 X 10 ⁻³	0.887 X 10 ⁻³	0.830 X 10 ⁻³	0.434 X 10 ⁻²	0.399 X 10 ⁻²	0.375 X 10 ⁻²	0.145 X 10 ⁻²	0.146 X 10 ⁻²	0.637 X 10 ⁻²	0.293 X 10 ⁻²	0.256 X 10 ⁻²	0.296 X 10 ⁻²	0.256 X 10 ⁻²	0.120 X 10 ⁻¹	0.112 X 10 ⁻¹	0.112 X 10 ⁻¹
0.426 X 10 ⁻³	0.398 X 10 ⁻³	0.399 X 10 ⁻³	0.437 X 10 ⁻³	0.399 X 10 ⁻³	0.374 X 10 ⁻³	0.195 X 10 ⁻³	0.180 X 10 ⁻²	0.169 X 10 ⁻²	0.646 X 10 ⁻³	0.650 X 10 ⁻³	0.283 X 10 ⁻²	0.127 X 10 ⁻²	0.112 X 10 ⁻²	0.129 X 10 ⁻²	0.111 X 10 ⁻²	0.522 X 10 ⁻²	0.488 X 10 ⁻²	0.488 X 10 ⁻²
0.189 X 10 ⁻³	0.176 X 10 ⁻³	0.177 X 10 ⁻³	0.191 X 10 ⁻³	0.177 X 10 ⁻³	0.166 X 10 ⁻³	0.866 X 10 ⁻³	0.795 X 10 ⁻²	0.748 X 10 ⁻²	0.283 X 10 ⁻³	0.285 X 10 ⁻³	0.124 X 10 ⁻²	0.574 X 10 ⁻³	0.480 X 10 ⁻³	0.555 X 10 ⁻³	0.479 X 10 ⁻³	0.224 X 10 ⁻²	0.210 X 10 ⁻²	0.210 X 10 ⁻²
0.704 X 10 ⁻⁴	0.658 X 10 ⁻⁴	0.660 X 10 ⁻⁴	0.714 X 10 ⁻⁴	0.660 X 10 ⁻⁴	0.618 X 10 ⁻⁴	0.323 X 10 ⁻³	0.297 X 10 ⁻²	0.279 X 10 ⁻²	0.105 X 10 ⁻³	0.105 X 10 ⁻³	0.458 X 10 ⁻³	0.199 X 10 ⁻³	0.174 X 10 ⁻³	0.201 X 10 ⁻³	0.174 X 10 ⁻³	0.815 X 10 ⁻³	0.761 X 10 ⁻³	0.761 X 10 ⁻³
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.0978	0.258	0.277	0.135	0.277	0.910	0.254	0.343	0.738	0.173	0.203	0.299	0.106	0.051	0.146	0.989	0.27	0.365	0.793
0.0483	0.127	0.137	0.0666	0.137	0.449	0.125	0.169	0.364	0.0876	0.103	0.150	0.0569	0.061	0.0782	0.528	0.141	0.191	0.418
23.91	23.70	23.71	23.91	23.71	23.54	119.5	117.5	116.21	14.92	14.93	75.12	8.386	8.135	8.405	8.133	42.38	41.62	41.65
48.40	48.03	48.34	48.47	48.04	47.72	242.9	238.7	235.9	29.50	29.53	149.6	15.67	15.75	15.73	15.24	81.26	79.50	78.97
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.679	1.668	1.650	1.650	1.665	1.666	7.558	7.858	7.963	1.67	1.66	7.53	1.66	1.644	1.634	1.644	6.68	7.046	7.704
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.274	0.256	0.256	0.277	0.256	0.240	1.255	1.153	1.085	0.265	0.267	1.16	0.291	0.257	0.297	0.257	0.202	0.123	0.123
0.0462	0.0138	0.0138	0.0467	0.0138	0.236 X 10 ⁻²	0.212	0.0622	0.0107	0.0194	0.0195	0.0851	0.0494	0.253 X 10 ⁻²	0.0501	0.253 X 10 ⁻²	0.202	0.606 X 10 ⁻¹	0.111 X 10 ⁻¹

- OHL -

TABLE B
"CLEAN CORE" REACTORS - MANGANESE SULFATE IN BLANKET
TWO GROUP - TWO REGION CALCULATIONS BY ORACLE
STAINLESS STEEL CLAD ELEMENTS
420°F CORE TEMPERATURE

Case No.	20	21	22	23	24	25	26	27	28	29	30	31	32	33
Reactor Radius, CM	30	30	30	30	60	60	60	60	60	60	60	80	80	80
Thickness of Shell between Core and Blanket	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Metal / Total Vol. Ratio	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Thermal Absorption Cross Section, CM ⁻¹ of Poison	0.02	0.0223	0.05	0.50	0.02	0.05	0.50	0.02	0.02	0.05	0.50	0.02	0.05	0.50
Thermal Neutron Flux	0.189 x 10 ⁻¹	0.189 x 10 ⁻¹	0.189 x 10 ⁻¹	0.189 x 10 ⁻¹	0.117 x 10 ⁻¹	0.170 x 10 ⁻¹	0.175 x 10 ⁻¹	0.923 x 10 ⁻²	0.109 x 10 ⁻¹	0.110 x 10 ⁻¹	0.114 x 10 ⁻¹	0.801 x 10 ⁻²	0.814 x 10 ⁻²	0.848 x 10 ⁻²
	0.177 x 10 ⁻¹	0.177 x 10 ⁻¹	0.176 x 10 ⁻¹	0.175 x 10 ⁻¹	0.111 x 10 ⁻¹	0.113 x 10 ⁻¹	0.118 x 10 ⁻¹	0.874 x 10 ⁻²	0.104 x 10 ⁻¹	0.105 x 10 ⁻¹	0.109 x 10 ⁻¹	0.770 x 10 ⁻²	0.781 x 10 ⁻²	0.811 x 10 ⁻²
	0.142 x 10 ⁻¹	0.142 x 10 ⁻¹	0.141 x 10 ⁻¹	0.138 x 10 ⁻¹	0.944 x 10 ⁻²	0.953 x 10 ⁻²	0.969 x 10 ⁻²	0.739 x 10 ⁻²	0.908 x 10 ⁻²	0.915 x 10 ⁻²	0.931 x 10 ⁻²	0.680 x 10 ⁻²	0.689 x 10 ⁻²	0.704 x 10 ⁻²
	0.449 x 10 ⁻²	0.937 x 10 ⁻²	0.913 x 10 ⁻²	0.865 x 10 ⁻²	0.696 x 10 ⁻²	0.690 x 10 ⁻²	0.673 x 10 ⁻²	0.536 x 10 ⁻²	0.708 x 10 ⁻²	0.707 x 10 ⁻²	0.702 x 10 ⁻²	0.544 x 10 ⁻²	0.545 x 10 ⁻²	0.545 x 10 ⁻²
	0.697 x 10 ⁻²	0.674 x 10 ⁻²	0.620 x 10 ⁻²	0.624 x 10 ⁻²	0.493 x 10 ⁻²	0.429 x 10 ⁻²	0.290 x 10 ⁻²	0.261 x 10 ⁻²	0.453 x 10 ⁻²	0.432 x 10 ⁻²	0.342 x 10 ⁻²	0.368 x 10 ⁻²	0.350 x 10 ⁻²	0.299 x 10 ⁻²
	0.717 x 10 ⁻²	0.672 x 10 ⁻²	0.394 x 10 ⁻²	0.443 x 10 ⁻²	0.549 x 10 ⁻²	0.324 x 10 ⁻²	0.364 x 10 ⁻²	0.323 x 10 ⁻²	0.427 x 10 ⁻²	0.244 x 10 ⁻²	0.282 x 10 ⁻²	0.374 x 10 ⁻²	0.216 x 10 ⁻²	0.252 x 10 ⁻²
	0.389 x 10 ⁻²	0.360 x 10 ⁻²	0.192 x 10 ⁻²	0.203 x 10 ⁻²	0.314 x 10 ⁻²	0.159 x 10 ⁻²	0.166 x 10 ⁻²	0.147 x 10 ⁻²	0.228 x 10 ⁻²	0.116 x 10 ⁻²	0.128 x 10 ⁻²	0.201 x 10 ⁻²	0.104 x 10 ⁻²	0.115 x 10 ⁻²
	0.156 x 10 ⁻²	0.144 x 10 ⁻²	0.745 x 10 ⁻³	0.773 x 10 ⁻³	0.177 x 10 ⁻²	0.614 x 10 ⁻³	0.632 x 10 ⁻³	0.560 x 10 ⁻³	0.909 x 10 ⁻³	0.447 x 10 ⁻³	0.489 x 10 ⁻³	0.807 x 10 ⁻³	0.398 x 10 ⁻³	0.437 x 10 ⁻³
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0.846 x 10 ⁻¹	0.847 x 10 ⁻¹	0.860 x 10 ⁻¹	0.884 x 10 ⁻¹	0.373 x 10 ⁻¹	0.381 x 10 ⁻¹	0.401 x 10 ⁻¹	0.764 x 10 ⁻¹	0.254 x 10 ⁻¹	0.347 x 10 ⁻¹	0.360 x 10 ⁻¹	0.244 x 10 ⁻¹	0.248 x 10 ⁻¹	0.260 x 10 ⁻¹
	0.790 x 10 ⁻¹	0.791 x 10 ⁻¹	0.801 x 10 ⁻¹	0.821 x 10 ⁻¹	0.354 x 10 ⁻¹	0.361 x 10 ⁻¹	0.378 x 10 ⁻¹	0.769 x 10 ⁻¹	0.327 x 10 ⁻¹	0.332 x 10 ⁻¹	0.343 x 10 ⁻¹	0.235 x 10 ⁻¹	0.238 x 10 ⁻¹	0.248 x 10 ⁻¹
	0.636 x 10 ⁻¹	0.637 x 10 ⁻¹	0.640 x 10 ⁻¹	0.647 x 10 ⁻¹	0.300 x 10 ⁻¹	0.303 x 10 ⁻¹	0.311 x 10 ⁻¹	0.727 x 10 ⁻¹	0.285 x 10 ⁻¹	0.288 x 10 ⁻¹	0.294 x 10 ⁻¹	0.207 x 10 ⁻¹	0.209 x 10 ⁻¹	0.215 x 10 ⁻¹
	0.420 x 10 ⁻¹	0.419 x 10 ⁻¹	0.415 x 10 ⁻¹	0.406 x 10 ⁻¹	0.221 x 10 ⁻¹	0.220 x 10 ⁻¹	0.216 x 10 ⁻¹	0.165 x 10 ⁻¹	0.222 x 10 ⁻¹	0.222 x 10 ⁻¹	0.222 x 10 ⁻¹	0.166 x 10 ⁻¹	0.166 x 10 ⁻¹	0.169 x 10 ⁻¹
	0.183 x 10 ⁻¹	0.182 x 10 ⁻¹	0.175 x 10 ⁻¹	0.158 x 10 ⁻¹	0.130 x 10 ⁻¹	0.125 x 10 ⁻¹	0.113 x 10 ⁻¹	0.941 x 10 ⁻²	0.148 x 10 ⁻¹	0.146 x 10 ⁻¹	0.140 x 10 ⁻¹	0.116 x 10 ⁻¹	0.115 x 10 ⁻¹	0.110 x 10 ⁻¹
	0.640 x 10 ⁻²	0.636 x 10 ⁻²	0.610 x 10 ⁻²	0.554 x 10 ⁻²	0.521 x 10 ⁻²	0.503 x 10 ⁻²	0.453 x 10 ⁻²	0.402 x 10 ⁻²	0.391 x 10 ⁻²	0.365 x 10 ⁻²	0.350 x 10 ⁻²	0.330 x 10 ⁻²	0.326 x 10 ⁻²	0.313 x 10 ⁻²
	0.293 x 10 ⁻²	0.292 x 10 ⁻²	0.280 x 10 ⁻²	0.254 x 10 ⁻²	0.239 x 10 ⁻²	0.203 x 10 ⁻²	0.208 x 10 ⁻²	0.184 x 10 ⁻²	0.170 x 10 ⁻²	0.167 x 10 ⁻²	0.161 x 10 ⁻²	0.151 x 10 ⁻²	0.149 x 10 ⁻²	0.144 x 10 ⁻²
	0.112 x 10 ⁻²	0.111 x 10 ⁻²	0.107 x 10 ⁻²	0.967 x 10 ⁻³	0.911 x 10 ⁻³	0.878 x 10 ⁻³	0.791 x 10 ⁻³	0.702 x 10 ⁻³	0.648 x 10 ⁻³	0.638 x 10 ⁻³	0.612 x 10 ⁻³	0.579 x 10 ⁻³	0.569 x 10 ⁻³	0.549 x 10 ⁻³
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0.130	0.130	0.132	0.136	0.093	0.093	0.094	0.0905	0.0921	0.0923	0.0927	0.090	0.0899	0.09
	0.0847	0.0845	0.0863	0.0904	0.0473	0.048	0.0483	0.0447	0.0462	0.0464	0.0468	0.0439	0.0438	0.044
	7.25	7.24	7.11	6.82	23.46	23.30	22.78	39.86	23.12	23.11	23.03	39.83	39.90	39.96
	11.21	11.17	10.88	10.28	46.24	45.79	44.42	80.81	46.06	45.96	45.99	81.61	81.67	81.56
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2.93	2.95	2.08	3.26	2.31	2.54	2.96	2.704	1.752	1.95	2.36	1.53	1.72	2.15
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0.055	0.0527	0.040	0.0134	0.079	0.0667	0.037	0.036	0.036	0.035	0.035	0.037	0.0344	0.0398
	0.979	0.974	0.933	0.847	0.797	0.769	0.693	0.614	0.567	0.559	0.536	0.505	0.499	0.479
	0.153	0.140	0.072	0.0075	0.124	0.0994	0.0061	0.0054	0.0888	0.0432	0.0047	0.0788	0.0385	0.0042

TABLE C*
"CLEAN CORE" REACTORS - INDIUM SULFATE IN BLANKET
TWO GROUP - TWO REGION CALCULATIONS BY ORACLE
STAINLESS STEEL CLAD ELEMENTS - 450°F CORE TEMPERATURE
1 CM THICK SHELL BETWEEN CORE AND BLANKET

Case No.	35	36	37	38
Reactor Radius, CM.	40	40	60	60
Metal/Total Vol. Ratio	0.20	0.20	0.20	0.20
Thermal Absorption Cross Section of Poison, CM ⁻¹	0.05	0.20	0.05	0.20
Thermal Neutron Flux at Center of Core	0.168 X 10 ⁻¹	0.170 X 10 ⁻¹	0.134 X 10 ⁻¹	0.136 X 10 ⁻¹
Thermal Neutron Flux at Core Radius/4	0.158 X 10 ⁻¹	0.159 X 10 ⁻¹	0.124 X 10 ⁻¹	0.126 X 10 ⁻¹
Thermal Neutron Flux at Core Radius/2	0.138 X 10 ⁻¹	0.130 X 10 ⁻¹	0.987 X 10 ⁻²	0.995 X 10 ⁻²
Thermal Neutron Flux at Core Radius/ 4/3	0.901 X 10 ⁻²	0.889 X 10 ⁻²	0.631 X 10 ⁻²	0.629 X 10 ⁻²
Thermal Neutron Flux at Core Radius	0.391 X 10 ⁻²	0.298 X 10 ⁻²	0.216 X 10 ⁻²	0.165 X 10 ⁻²
Thermal Neutron Flux at Core Radius + Shell Thickness + Blanket Thickness /4	0.117 X 10 ⁻²	0.109 X 10 ⁻³	0.638 X 10 ⁻³	0.582 X 10 ⁻⁴
Thermal Neutron Flux Core Radius + Shell Thickness + Blanket Thickness /2	0.526 X 10 ⁻³	0.430 X 10 ⁻⁴	0.293 X 10 ⁻³	0.239 X 10 ⁻⁴
Thermal Neutron Flux Core Radius + Shell Thickness + Blanket Thickness 4/3	0.203 X 10 ⁻³	0.166 X 10 ⁻⁴	0.115 X 10 ⁻³	0.937 X 10 ⁻⁵
Thermal Neutron Flux at Extrapolated Boundary	0	0	0	0
Fast Neutron Flux at Center of Core	0.605 X 10 ⁻¹	0.614 X 10 ⁻¹	0.435 X 10 ⁻¹	0.444 X 10 ⁻¹
Fast Neutron Flux at Core Radius/4	0.568 X 10 ⁻¹	0.576 X 10 ⁻¹	0.405 X 10 ⁻¹	0.413 X 10 ⁻¹
Fast Neutron Flux at Core Radius /2	0.468 X 10 ⁻¹	0.491 X 10 ⁻¹	0.322 X 10 ⁻¹	0.326 X 10 ⁻¹
Fast Neutron Flux at Core Radius/ 4/3	0.323 X 10 ⁻¹	0.321 X 10 ⁻¹	0.206 X 10 ⁻¹	0.205 X 10 ⁻¹
Fast Neutron Flux at Core Radius	0.167 X 10 ⁻¹	0.161 X 10 ⁻¹	0.847 X 10 ⁻²	0.815 X 10 ⁻²
Fast Neutron Flux at Core Radius + Shell Thickness + Blanket Thickness /4	0.302 X 10 ⁻²	0.292 X 10 ⁻²	0.164 X 10 ⁻²	0.157 X 10 ⁻²
Fast Neutron Flux at Core Radius + Shell Thickness + Blanket Thickness /2	0.142 X 10 ⁻²	0.139 X 10 ⁻²	0.788 X 10 ⁻³	0.954 X 10 ⁻³
Fast Neutron Flux at Core Radius + Shell Thickness + Blanket Thickness / 4/3	0.551 X 10 ⁻³	0.532 X 10 ⁻³	0.313 X 10 ⁻³	0.300 X 10 ⁻³
Fast Neutron Flux at Extrapolated Boundary	0	0	0	0
$\sum_{2c}^T$ Total Thermal Macroscopic Absorption Cross Section for Core	0.105	0.106	0.096	0.096
$\sum_{2c}^F$ Thermal Macroscopic Absorption Cross Section of Fuel in Core	0.059	0.060	0.050	0.050
A _{T2c} ^F Thermal Absorptions in Fuel in Core	11.04	10.92	22.10	21.49
A _{T2c} ^T Total Thermal Absorptions in Core	19.62	19.31	42.51	41.20
A _{1c} ^F Resonance Absorptions in Core	0	0	0	0
A _{T2B} ^F Thermal Absorptions in Fuel in Blanket	0	0	0	0
A _{T2B} ^T Total Thermal Absorptions in Blanket	1.96	0.917	2.24	1.075
A _{1B} Resonance Absorptions in Blanket	0.953	2.12	1.074	2.37
A _s Absorptions in Shell	0.039	0.019	0.0484	0.0238
L ₁ Fast Leakage	0.718	0.693	0.757	0.725
L ₂ Thermal Leakage	0.029	0.0024	0.0309	0.00250

APPENDIX D

RECORD OF CORRESPONDENCE

Food Sterilization Reactor--
A Summer Problem for an ORSORT Student Group

As indicated by the attached letter, the Quartermaster Corps is very interested in the development of a nuclear reactor to supply gamma radiation for the sterilization of food.

The problem assignment consists of the choice, conceptual design, and evaluation of a reactor-irradiation system capable of meeting the requirements in the attached letter from Mr. Siu to Mr. Horner. As implied in the letter, some of the requirements may be altered.

A copy of a pertinent literature survey by J. W. Ullman is also attached.

It may be assumed initially that a cost of about 2¢ per pound is permissible.

The Quartermaster Corps has indicated a desire to supply as much information as possible on this problem. More information on their needs will be available before work on the problem begins, and, if desirable, a conference with representatives of the Quartermaster Corps can probably be held near the beginning of the problem period.

The primary aims are a reactor which produces gamma rays or gamma ray emitters and a method for using them to sterilize food. The production of power or other by-products should not be a consideration unless sufficient time remains in the study period after the primary goal is reached.

Advisors:	R. N. Lyon	- Reactor Exptl. Eng. Division	Phone 7305
	R. W. Peelle	- Shielding Division	Phone 6126
	H. R. Zeitlin	- Chem. Tech. Division	Phone 6394
	R. R. Bate	- (Liaison with Army)	Phone 6173

C
O
P
Y

QMGRT 400.112
Radiation

21 April 1955

Mr. Charles R. Horner
Division of Reactor Development
Atomic Energy Commission
Washington 25, D. C.

Dear Charles:

With reference to last week's conversation on the study of reactor design for radiation of foods at the Oak Ridge School, I had sent inquiries to the Food and Container Institute for the relevant processing parameters.

It may be several weeks before we will be able to provide data on which your study can firmly proceed. In the meantime, as you requested, here are some rough estimates to enable you to orient the problem generally:

1. Volume capacity- 40 tons per day
2. Operating time - 10 hours per day continuously,
5 days per week
3. Shutdown time - weekends
4. Size of radiated packages
Type a - 1 ft. diameter cylinders
Type b - sides of beef
5. Conveyor system - automatic
6. Processing time for radiation treatment - less than
5 minutes
7. Maximum size of reactor - 30 ft. cube.

With best regards.

Sincerely,

R. G. H. SIU
Technical Director
Research and Development Division
Office of Quartermaster General
Washington 25, D. C.

AIR MAIL

QUARTERMASTER FOOD AND CONTAINER INSTITUTE FOR THE ARMED FORCES
CHICAGO QUARTERMASTER DEPOT. U. S. ARMY
1819 West Pershing Road
Chicago 9, Illinois

In reply refer to
QMDIL-FL

28 June 1955

Dr. R. N Lyon
Reactor Experimental Eng. Div.
Oak Ridge National Laboratory
P. O. Box P
Oak Ridge, Tennessee

Dear Dr. Lyon:

Reference is made to the conference held on 17 May 1955 at Oak Ridge to discuss the possibility of designing a reactor as a gamma source for the Army. At the time a question was asked as to what neutron flux could be tolerated if foods were to be irradiated.

Measurements made by Dr. Robert H. Lewis, at the Materials Testing Reactor, indicate that foods irradiated by spent fuel rods have been exposed to fluxes of 10^4 neutrons/cm²/sec for times averaging about 25 minutes without the production of any measurable increase in activity in the samples of food or their containers. Since this irradiation was conducted in the canal with the foods shielded from the rods by the canal water and cadmium sheets, it is assumed that this flux was caused by the (gamma, n) reaction of high energy gamma photons with the deuterium in the canal water.

Based on some rough calculations made by Dr. Lewis, Mr. Donald Hunke of Phillips Petroleum Company, and myself, it appears that, insofar as induced activity is concerned, a neutron flux of about 10^5 neutrons/cm²/second for periods of a half hour is considered safe. This figure is offered as a guide, and we expect to have more definite information available in the near future. This is based only on possible induced activity and not on possible changes in flavor or formation of toxic compounds.

I hope that I shall be able to visit your group again soon. This problem has evoked considerable interest among the personnel in our project.

FOR THE COMMANDANT:

BELMONT S. EVANS, JR.
Lt. Colonel, CmlC
Nuclear Effects Engineer

C
O
P
Y

QUARTERMASTER FOOD AND CONTAINER INSTITUTE FOR THE ARMED FORCES
CHICAGO QUARTERMASTER DEPOT. U. S. ARMY
1819 West Pershing Road
Chicago 9, Illinois

In reply refer to:
QMDIL-FL

26 May 1955

Dr. R. N. Lyon
Reactor Experimental
Engineering Division
Oak Ridge National Lab.
Oak Ridge, Tennessee

Dear Dr. Lyon:

The visit of Colonel William D. Jackson, Dr. Ralph G. H. Siu, Lt. Colonel Truman F. Cook, and myself to Oak Ridge on 17 May was a most interesting one, and we appreciated this opportunity to discuss our problems of locating an intensive gamma source for the radiation sterilization of foods and other possible uses by the Army.

At the time of our discussion several questions were raised concerning some of our requirements for the source. First, insofar as dose limits are concerned, we would like to have the actual dose delivered to be within the limits of -0 to +25% of the specified dose. Concerning the size of items to be irradiated, in addition to No. 2 and No. 10 cans, we would like to be able to handle cartons 6" x 16" x 20" (the size normally used to ship meat cuts) and possibly cartons 7 1/4" x 12-3/4" x 10" (the size containing six No. 10 cans).

The elements which constitute almost entirely foods of interest to us are:

C, H, O, N, Ca, Mg, K, Na, P, Cl, S, Fe, Cu, Mn, Zn, and I.

Other "trace" elements that might possibly be of concern only if localized within the body are:

Co, Al, As, Br, F, B, Mo, and Si.

Inclosed are four (4) copies of a series of review articles which may be of assistance in giving you and your group an idea of the "status of the art."

QMDIL-FL

26 May 1955

Dr. R. N. Lyon, Oak Ridge National Lab., Oak Ridge, Tenn.

I have been selected to act as liaison between the Quartermaster Corps and your group. Please feel free to call on me for any additional information which you feel I may be able to furnish to aid the study.

FOR THE COMMANDANT:

/s/ Belmont S. Evans, Jr.

BELMONT S. EVANS, JR.
Lt. Colonel, CmlC
Nuclear Effects Engineer

1 Incl
Ref review
articles (4 cys)

cc: Dr. R. G. H. Siu, Wash. DC
Lt. Col T. F. Cook, Wash, DC

C
O
P
Y

July 14, 1955

Commandant
Quartermaster Food and Container
Institute for the Armed Forces
Chicago Quartermaster Depot, U. S. Army
1819 West Pershing Road
Chicago 9, Illinois

Attention: Lt. Colonel Belmont S. Evans, Jr.

Dear Colonel Evans:

Your letter of 28 June, 1955 addressed to Dr. R. N. Lyon has been passed on to us in the group studying the design of a gamma radiator reactor. I would like first to report on our progress and then to request your help in answering several specific questions.

We have made a number of preliminary calculations, and on the basis of these have decided to design the gamma radiator as a heterogeneous reactor in the core of which a solution of manganese sulfate is activated. The decision to pursue this design was somewhat arbitrary. We believe that a design employing gaseous fission products from a homogeneous reactor could be equally well developed. However, we have chosen the heterogeneous design in order

- a) to follow the established technology and operational characteristics of the heterogeneous reactor, and
- b) to avoid the necessity for local fuel processing inherent in the homogeneous design.

Other suggestions involved the use of fission gammas directly from the core or intermittent operation of a heterogeneous reactor core with exposure of meat to the fuel elements during periods of reactor shutdown. These suggestions have been abandoned in favor of the use of an activated coolant.

Lt. Colonel Belmont S. Evans, Jr.

July 14, 1955

We were interested in your estimate that a neutron flux of 10^5 neutrons/cm²/sec for exposure periods of a half hour would be permissible. This compares with our own estimate (also based upon induced activity) of permissible neutron flux equal to 2×10^4 neutrons/cm²/sec. Both estimates lead clearly (calculations made by this group) to the conclusion that it will not be desirable to try to use the direct fission gammas from the fluxes, but only with large attenuations of both.

The permissible neutron flux which we calculated was based upon the following:

- a) Ten minute exposure time,
- b) Twenty minute waiting time after exposure,
- c) An assumed counting ability of 0.01 (disintegrations)/sec/cm³
- d) An analysis of beef as reported in American Scientist 40 404 (1952).

We are interested in knowing more about the assumptions you used in obtaining an estimate of 10^5 neutrons/cm²/second.

We have another problem in this study with which you may be able to help. During the conference of May 17 a processing time of 5 to 10 minutes was specified. As our calculations have progressed, it has become apparent that this specification may have the effect of dictating a high reactor flux and possibly a high reactor power level. This is true in the heterogeneous activated coolant-reactor type which we have chosen to design. It may be true of other types as well. We are proceeding in our calculations by including processing time as a variable. Can you tell us why the 10 minute processing time was chosen and if there are any particular disadvantages to increasing the processing time to one hour or more? We believe that refrigeration of the irradiation room will be required to prevent a partial thaw of meat from gamma heating sensible heat gain.

There has been some discussion here about the 2¢ per pound processing cost which has been stated to be permissible. On what basis was this cost determined? Is it permissible in part because of reduced storage costs? How much of this cost must be justified by improved product quality?

Lt. Colonel Belmont S. Evans, Jr.

July 14, 1955

We are near the half way point in the time available to us to make this study. We would, in particular, appreciate a chance to discuss this problem with you again at Oak Ridge. However, if this cannot be arranged, your reply to the questions asked above will be quite helpful.

Very truly yours,

Edwin O. Guernsey
Reactor Exptl. Engr. Division
Building 9204-1, Y-12 Area

EOG:tkc

cc: R.G.H. Siu, Technical Director
Research and Development Division
Office of the Quartermaster General
Washington 25, D. C.

C
O
P
Y

QUARTERMASTER FOOD AND CONTAINER INSTITUTE FOR THE ARMED FORCES
CHICAGO QUARTERMASTER DEPOT. U. S. ARMY
1819 West Pershing Road
Chicago 9, Illinois

In Reply Refer To:
QMDIL-FL

22 July 1955

Mr. Edwin O. Guernsey
Reactor Exptl. Engr. Div.
Bldg. 9204-1, Y-12 Area
Oak Ridge National Lab.
Oak Ridge, Tennessee

Dear Mr. Guernsey:

I have received your letter of July 14 describing some of the progress which you have made in preparing the gamma radiator reactor. This is a problem which has evolved much interest among personnel with whom I have discussed it.

In order to discuss fully some of the questions which you have raised I have requested clearance to visit Oak Ridge on 28 and 29 July. During this visit I also hope to be able to see Dr. Livingston concerning dosimetry problems concerned with electron accelerators and also Dr. Hochanadel on problems of ceric-cerous dosimetry. I plan to stay at the hotel in Oak Ridge on the evening of 27 and 28 July and will attempt to contact you on the morning of the 28th in the Y-12 area. I would appreciate your leaving any special instructions for me at the hotel.

FOR THE COMMANDANT:

/s/ Belmont S. Evans, Jr.

BELMONT S. EVANS, JR.
Lt. Colonel, CmlC
Nuclear Effects Engineer

A I R M A I L

QUARTERMASTER FOOD AND CONTAINER INSTITUTE FOR THE ARMED FORCES
CHICAGO QUARTERMASTER DEPOT. U. S. ARMY
1819 West Pershing Road
Chicago 9, Illinois

In Reply Refer To:
QMDIL-FL

4 August 1955

Mr. Edwin O. Gurnsey
R. E. E. D.
Bldg. 9204-1, Y-12 Area
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Dear Mr. Gurnsey:

Reference our conference at Oak Ridge on 28 July 1955,
at which time several questions on costs were raised.

Insofar as cost of electricity to industrial users in
this area is concerned, the cost is 1.6 cents per kilowatt hour
plus an additional charge for the peak 15 minute load per month.

The average monthly utilization for the major packers
in Chicago averages between 4,500,000 and 5,000,000 kilowatt hour
per month. None of the representatives with whom I spoke felt
that under present conditions they would want to become involved
in the production and sale of power.

Concerning the Michigan reports which we mentioned, copies
of all those we have were also sent to the Technical Information
Service (R. L. Metter) at Oak Ridge. They are listed as reports on
Project M 943 (Utilization of Gross Fission Products) of the Engineering
Research Institute, University of Michigan, under AEC Contract number
AT (11-1) - 162.

I hope that this information will be of use to you at this
time. While time is short, I shall try to get any additional informa-
tion for you prior to your deadline, if you desire any.

I am looking forward to hearing your final report and I
hope to visit with your group again.

FOR THE COMMANDANT:

/s/ Belmont S. Evans, Jr.

BELMONT S. EVANS
Lt. Colonel, QMC
Radiation Sterilization Officer