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PRELIMINARY HAZARDS EVALUATION FOR ENRICHED URANIUM-THORIA (E-Q) LOADING - HANFORD IPD REACTORS

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PRELIMINARY HAZARDS EVALUATION FOR ENRICHED URANIUM-THORIA (E-Q) LOADING - HANFORD IPD REACTORS

R. Nilson, P. A. Carlson, and G. F. Owsley

INTRODUCTION

The General Electric Company, as contractor to the AEC at Hanford, is proposing to modify the fuel loading of one or more of the IPD production reactors for the purpose of producing "clean" U-233 as a coproduct with plutonium. The isotope U-233, with low (3-5 ppm) U-232 content, is expected to become a material with important nuclear applications. The IPD reactors are well suited to produce clean U-233.

A proposal to produce 200 kg of U-233 for critical experiments for the AEC's seed-and-blanket reactor program have been made in response to recent AEC inquries. The production of such large quantities of U-233, on the schedule requested, would require nearly full utilization of the IPD reactors for a period of abouc half a year. This report, therefore, is intended to evaluate the nuclear safety of the IPD reactors whose entire loadings have been altered to coproduce U-233 and Pu-239.

The coproduct loading will involve irradiating thorium oxide target elements. Excess reactivity to support the target material will be furnished by slightly enriched uranium, charged in tubes separate from the thoria. The expected fuel-to-target ratio is about 5.5 in the reactor cores and two in the reactor fringes.

A full technical hazards evaluation of the E-Q load is presently in preparation and will be issued as a supplement to the Hazards Summary Reports[1]. This treatment

1. Irradiation Processing Department Staff. Hazards Summary Reports, HW-74094 and HW-74095. 1963. (SECRET)

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covers only the highlights of the full report and is intended as an interim and preliminary evaluation.

SUMMARY AND CONCLUSIONS

The proposed modification of the Hanford IPD reactor fuel loadings to produce clean U-233 is not expected to result in an over-all nuclear safety status for these reactors which is significantly different from that for the present natural uranium fuel loadings. This opinion is drawn from preliminary information, a summary of which is presented below, and from the successful operation of the E-N reactor loading, a like loading to the E-Q in many respects.

1. The basic physics of the E-Q reactor will not be changed sufficiently to alter the inherent nuclear safety characteristics of the reactors.

2. The hydraulics and heat-transfer characteristics of the reactor will not be altered appreciably by the modification.

3. One principal difference is identified in the E-Q reactor which has a potential of making it a less-safe reactor. This is the fact that about 80 per cent of the reactor is loaded with enriched uranium. The potential for a loading or unloading error is thus increased, and the size of a loading error, capable of resulting in a serious outcome, is reduced. These possibilities have been recognized and several steps will be taken to give positive assurance that loading errors will not occur, and if they do occur, they will not be capable of leading to a serious outcome. What

4. With the exception of accidents associated with loading errors, the probabilities, protective measures, and outcomes of conceivable nuclear accidents in the E-Q reactor are expected to be essentially the same as those in the natural uranium reactor.

5. For the majority of the conceivable mechanical failure accidents, the probabilities, protective measures, and outcomes in the E-Q reactor are expected to be essentially the same as those in the natural uranium reactor. Higher equilibrium powers in fuel channels are expected to slightly increase the severity in the outcome of failures of inlet connectors, inlet nozzles, and outlet nozzles.

6. The sequence of events, outcome, and offsite consequences of the maximum credible accident, failure of an inlet crossheader, are found to be nearly identical to those for the natural uranium reactor loading.

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OVER-ALL HAZARDS EVALUATION

Basic Physics

The basic physics of the E-Q reactor differs little from that of the normal production reactor. In some respects, the physics will be similar to that of the enriched uranium-lithium (E-N) loading which is a similar fuel-and-target application in the Hanford reactors. The reactors will still operate as thermal reactors with the new loadings, and the physics models of thermal reactors should apply. Unlike the natural uranium loading, a significant fraction of neutrons will be absorbed in useful reactions which take place in target material separate and discrete from the fuel. The principal physics differences, as they bear on reactor safety, are associated with this rearrangement of fuel and target. In total, the modification is expected to result in reactor physics characteristics which should not lessen the inherent safety of the Hanford reactors.

The temperature coefficients are expected to change as follows:

1. The prompt temperature coefficient, associated with fuel heating, will remain negative, but the absolute magnitude is expected to be reduced by about 15 per cent because of the smaller U-238 inventory in the reactor. Such a reduction is not significant. The Doppler effect associated with the heating of the thorium oxide will also be negative, but the contribution to the over-all reactivity balance should be small due to the small fraction of thoria in the reactor and the low heat generation in this portion of the reactor loading.

2. The positive graphite temperature coefficient is expected to be increased by about 50 per cent for fresh fuel; however, the exposure-dependence of the coefficient will be markedly smaller due to the reduced importance of plutonium in the higher U-235 content fuel. The maximum value of the coefficient (at the end of the fuel cycle) should exceed the maximum value in the natural uranium loading by about ten per cent.

The exposure-dependent reactivity effects are expected to differ from those of a natural uranium loading as follows:

1. Xenon and samarium poisoning should be very nearly the same.

2. The buildup of fissile isotopes (Pu-239, e.g.) will be less effective in compensating for U-235 burnout, and it is expected that the reactivity transient as fuel exposure is increased will be flatter. This behavior was characteristic of the E-N reactor and resulted in a reactor with excellent operating ease.

The loss of coolant in the E-Q reactor during reactor operation will still result in a positive reactivity effect, but the accident should be less autocatalytic than in the uranium-only lattice. The reason for this is that voiding of the coolant in the thoria columns is expected to be delayed by about 30 seconds after the coolant in the fuel columns has boiled out. Thus, prompt automatic reactor shutdown need only turn around the reactivity surge associated with loss of coolant in the fueled channels. This surge is calculated to be less than the total surge presently accompanying loss of coolant in a predominantly natural uranium fueled reactor. The reactivity effect of coolant loss in the thoria channels is also calculated to be positive, but it has no effect on the consequences of the accident due to its delayed action and relatively small magnitude.

Control requirements in the shutdown reactor to meet dry reactor reactivity condition in the event of coolant loss may be increased somewhat due to the slightly larger total void coefficient (fuel and thoria coolant loss), but this should result only in the reactor efficiency loss related to use of additional supplemental control.

Other physics-related characteristics of the E-Q reactor should differ little from those of the present reactor loadings.

1. Nuclear strengths of the reactors' control and safety systems should not be changed, although care will be taken in the initial E-Q loading to place the thoria columns away from control and safety system channels because of the low importance of these channels on the neutron multiplication of the reactor. Control rod calibrations will be part of the initial startup tests.

2. The reactor kinetics should differ little, since the delayed neutron fractions and neutron lifetime will be virtually unchanged.

3. Startup and shutdown reactivity transients should be of like form to those in the present reactor operation, but will probably be more pronounced due to the larger net temperature coefficient.

4. Despite a higher graphite temperature coefficient, the fact that the neutron flux in the fuel will be lower should result in an operation which does not differ significantly from that at present with respect to thresholds for xenon-temperature instabilities.

One principal difference is identified in the E-Q reactor which has a potential of making it a less-safe reactor. This is the fact that about 80 per cent of the reactor is loaded with enriched uranium, the excess reactivity being compensated for by the thorium oxide targets. The potential for a loading or unloading error is thus increased, and the size of a loading error, capable of resulting in a serious outcome, is reduced. These possibilities have been recognized and several steps will be taken to give positive assurance that loading errors cannot occur, and if they do occur, they will not be capable of leading to a serious outcome.

Basic Engineering

The enriched uranium fuel elements and thorium oxide target elements will be designed so that the current total reactor coolant flow rates will be retained with E-Q loadings. Thus, at the 95 C bulk outlet coolant temperature limit, the reactor power level capability would be unchanged. However, the distribution of coolant

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flow to the process channels and the heat generation rates of individual fuel columns will vary. The central-zone enriched fuel columns must operate at tube powers which are about 16 per cent higher than those in the reactors with natural uranium loadings to compensate for the power lost in the process channels loaded with thoria.

By orificing and design of fuel and thoria elements, the coolant flow will be reduced to the low power thoria columns and increased to the enriched fuel columns to maintain fuel and coolant temperatures within safety and material limits. Design calculations show that the coolant flow rates in the fuel columns should increase 13-20 per cent with the coolant temperature increasing no more than four per cent.

Calculations show that the effect of these revised operating conditions on the steady-state heat transfer characteristics of the individual process channels would be minor.

1. The coolant flow rates in fuel columns are to be increased so that the higher fuel heat generation rates can be obtained with only a modest increase in process channel coolant temperatures.

2. The maximum uranium core temperatures will be less than 400 C, well below the limiting uranium alpha-beta transformation temperature (660 C).

3. Peak aluminum cladding surface temperatures will be below those required for nucleate boiling.

4. Peak fuel surface heat fluxes should be only 20-30 per cent of the calculated burnout heat flux at hot channel operating conditions.

5. The thorium oxide target elements will account for only a small fraction of the total heat liberated during the operation of the reactor. At maximum target element exposures, the specific power in a centrally-loaded thoria column should reach about 10 kw/ft, and the maximum calculated thoria core temperature should be less than 1000 C, well below the oxide melting temperature of about 3200 C. Surface temperatures should be less than 50 C because of the low heat generation rates and low coolant temperatures in the thoria columns.

The heat transfer characteristics of the process channels during emergency flow-loss conditions and the protection against flow loss provided by the pressure monitor system should not change appreciably with E-Q reactor loadings.

1. The number of central-zone process channels which would be subject to flow instability would be decreased because about 15 per cent of the process channels would be loaded with thoria target elements.

2. Laboratory tests verify that present individual process channel protection methods will provide the same high degree of protection against melting due to flow-loss accidents in individual fuel columns in E-Q loadings as they do currently in the reactors loaded with natural uranium. These tests

have been run with power levels up to 30 per cent higher than maximum tube powers expected in E-Q loadings.

The bulk reactor steady-state operating conditions will be unchanged by E-Q loadings. The higher tube powers would, however, reduce the adequacy of the last-ditch coolant system, which is now limited by the requirement that process channel coolant outlet temperatures must be maintained 5 C below the outlet cross-header boiling temperatures. Calculations show that the reactors will operate closer to their last-ditch coolant system power limits, but capacity will still be adequate.

Nuclear Accidents

With the exception of accidents associated with loading errors, the probabilities, protective measures, and outcomes of conceivable nuclear accidents in the E-Q reactor are expected to be essentially the same as those in the natural uranium reactor[1].

The outcome of a significant loading error in the predominantly natural uranium reactor was discussed in considerable detail in Reference 1. As was indicated, charging about 70 to 80 tubes of enriched uranium fuel in a block could override the vertical safety rod system and result in the reactor becoming critical. (This was not considered a credible event.) In the E-Q reactor, the same result can be obtained by replacing about 15 columns of thoria with enriched uranium fuel or by an accidental ejection of thoria from a somewhat larger number of columns. Both these events would introduce a rather large amount of positive reactivity in a relatively short time.

Detailed evaluation, including consideration of new procedures and safeguards, indicate that the number of independent events which must combine in these accidents to result in a hazardous outcome are so numerous that a nuclear accident initiated by a loading error is not considered credible.

Some of the possible errors are as follows:

1. Failure to load or unload target and fuel columns in proper sequence resulting in enriched fuel without compensating poison.

2. Fuel and target identification errors.

3. Inadvertent loading of fuel in target tubes.

4. Blank thoria targets or wrong composition.

5. Flush of thoria columns already charged.

The potential outcome of inadvertent criticality events in the E-Q reactor could be greater than in the natural uranium reactor. Maximum reactivity insertion rates introduceable by loading errors will be about six times greater. Thus,

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the driving force for an excursion would be considerably greater, and the time available for corrective action shorter. In addition, if the reactor had been misloaded (in a local region), not to the point of criticality but sufficiently to permit criticality during safety rod withdrawal in a subsequent startup, the rate at which positive reactivity would be added by rod withdrawal would also be materially increased. Again, the resulting excursion would be more severe.

It is obvious, in view of these new accident possibilities, that reliable safeguards, of considerable depth, be adopted in the E-Q reactor to prevent inadvertent attainment of criticality and to provide prompt, automatic corrective measures should it occur. Four basically different safeguards will be used.

First, precautions will be taken to assure that loading or unloading errors will be reduced to an absolute minimum.

1. All thoria target elements will be weighed to determine that the specified density is correct.

2. A statistically valid sample of finished elements will be tested in the Hanford Test Reactor for thermal neutron blackness.

3. Enriched uranium fuel elements will be six inches in length, and natural uranium fuel elements will be eight inches in length. The thoria targets will be also six inches in length, but will be solid rods instead of tubular. The weight of a thoria target will be less than half that of a fuel element.

4. Process channels to be loaded with thoria will be positively identified by such techniques as color-coating the caps (on both reactor faces) and using special seals.

5. Only thoria or enriched uranium but <u>not</u> both will be available on the front work platform for loading at any one time, thus precluding the possibility of the operating crew charging the wrong material.

6. All thoria columns will be loaded first in the initial loading and unloaded last in a return of the reactor to a different loading. When the loading pattern is to be altered in a localized region such that fuel replaces thoria and thoria replaces fuel, the thoria will always be charged first.

7. As with the natural uranium load, clearly written procedures and column makeup instructions will be provided, and effective cross-checking will be employed by responsible operating personnel. In addition, an independent observer, with no operational assignment, will be responsible for assuring that the proper material is charged into each process channel in the prescribed tube loading sequence. He will have the authority to stop the charging operation at any time.

8. Flushing of thoria from columns already loaded will be minimized by permitting only a safe number of rear-face process channel caps off at any one time. Flushing charged material could result if valving procedures were not followed prior to cap removal and the process water pressure were inadvertently raised to operating conditions.

Second, instrumentation will be in service to monitor the shutdown flux level and warn if a significant approach to critical occurs.

1. The reactor subcritical monitors will be frequently observed during all charge-discharge operations to detect changes in the subcritical flux level or malfunction of the monitors.

2. An alarm will be placed on the instruments to detect a rise in neutron level of more than a factor of two to four.

3. If an alarm is received, all charge-discharge activity will be stopped and will not be resumed until the cause has been determined and corrected.

Third, means will be provided to quickly shut the reactor down should the reactor actually achieve a critical condition during charge-discharge.

1. Several safety rods, sufficient to override the excess reactivity caused by the loading error, will be held in scram readiness.

2. The rods will be chosen to provide the geometric coverage necessary to be effective in controlling localized zones of excessive neutron multiplication.

Fourth, safety rod withdrawal rates and sequences will be specified and controlled by procedures to assure that, in the event of early critical during safety rod withdrawal, the following conditions can be met.

1. Normal startup control techniques can limit the power rise in ample time to permit an orderly rise to power within normal process safety limits.

2. In the event of failure to make such corrective control action, an automatic safety rod scram initiated by the flux monitor set at the startup trip point could terminate the power rise at one per cent or less of the normal reactor power level.

Mechanical Failure Accidents

For the majority of the conceivable mechanical failure accidents, the probabilities, protective measures, and outcomes in the E-Q reactor are expected to be essentially the same as those in the natural uranium reactor[1]. Higher equilibrium powers in fuel channels are expected to slightly increase the severity in the outcome of failures of inlet connectors, inlet nozzles, and outlet nozzles.

1. Following the complete failure of an inlet hydraulic connector, reverse coolant flow will be established in the process channel affected because of the pressure difference between the outlet crossheader and the point of failure at the tube inlet. If the pressure difference is large enough, the fuel in the affected channel will be adequately cooled provided there is an immediate scram upon the failure. (Each process channel is provided

 [redacted]

with an inlet pressure monitor.) The pressure difference required to avoid fuel damage is a function of power level, hydraulic resistance of the fuel, and hydraulic resistance of the inlet and outlet hardware. Because of the higher fuel column powers in the E-Q reactor, a higher pressure differential would be required for adequate reverse coolant flow. The outlet header pressures, which provide the driving force for coolant flow in this accident, will not change with the new loadings. Thus, a higher probability for fuel burnout would exist following the sudden and complete failure of an inlet hydraulic connector on a fuel column than exists in current operations. The total number of process channels subject to fuel burnout from inlet connector failures should not be increased, however; since 15 per cent of the process channels will contain thoria.

2. The outcome of an inlet nozzle failure in terms of heat-transfer burnout would be similar to that of the inlet connector failure described above except that the reverse coolant flow rates for a given outlet header pressure would be greater because of the lower hydraulic resistance at the point of failure. Thus, more fuel elements could survive the inlet connector failure. However, an importance difference exists between the two accidents. The boiling which would develop in early stages of the nozzle failure accident may develop sufficient pressure to expel fuel elements from the process tubes. The fuel elements from an E-Q reactor would have greater sensible and decay heat than fuel elements operating at current reactor conditions due to their higher specific powers. The likelihood for melting in the front work spaces would, therefore, be increased somewhat.

3. The complete failure of an outlet nozzle assembly or loss of an outlet nozzle cap during reactor operation would cause the contents of the process tube to flush from the process tube. Most or all of the fuel or target elements would fall into the irradiated fuel storage basins where they would be adequately cooled. However, one or more elements might become lodged in the discharge area piping and not reach the basin. If these were fuel elements, they would not be adequately cooled by the ambient air. Fuel elements from an E-Q reactor would reach the melting temperature of the aluminum cladding, under such conditions, in 150-350 seconds, about 50 seconds sooner than fuel elements from current operations. It is also more likely that the uranium would eventually reach the melting temperature. The cooling provided by installed fog sprays would be sufficient to arrest the fuel temperature rise and to reduce fuel element surface temperatures to less than 100 C in an interval of five to eight minutes. Thus, if flushed fuel elements were lodged in the discharge area piping, melting of the fuel cladding can be avoided if fog-spray cooling is initiated within 150 seconds. In present operations, 200 seconds are available to take this action. Should the outlet nozzle failure cause the discharge of a thorium oxide target column during equilibrium reactor operation, the rapid removal of poison from the reactor would initiate a reactor power rise. However, the inlet pressure to each thorium oxide target charge is to be monitored, and the reactor would be

[redacted]

scrammed in such an event. The scram should limit the reactor power surge, and outlet coolant temperatures should not increase to the point where over-pressurization would damage the reactor effluent system. Power levels in enriched fuel columns adjacent to the empty thoria columns should rise less than five per cent before the surge is terminated by the scram. No damage would be caused in adjacent fuel columns.

Other General Hazards

The E-Q modification will not alter the general hazards associated with fire, earthquake, flood, etc. However, the increased use of enriched uranium will intensify storage requirements necessary to maintain current criticality limits on enriched uranium storage. The basin storage capacity for irradiated enriched uranium is more than adequate at all reactor areas to meet the E-Q requirements. The current storage capacity for unirradiated enriched uranium is adequate at all small reactor areas, but use of some of the natural uranium storage space at the K Reactors would be necessary to meet the E-Q requirements.

Since the procedures for out-of-reactor handling of enriched material have been in effect for several years and have been demonstrated to provide adequate assurance against attaining a critical mass, it is considered that the increased use of enriched uranium will not result in any increased storage hazard.

Maximum Credible Accident

The maximum credible accident for the Hanford IPD reactors has been identified as the failure of an inlet crossheader[1]. In the E-Q reactor, this failure is still considered the maximum credible accident. The sequence of events, outcome, and offsite consequence of the accident in the E-Q reactor are found to be nearly identical to those described in detail in Reference 1.

The accident details are beiefly repeated here. In the event of a sudden and complete failure of an inlet crossheader, the coolant pressure would suddenly drop, reducing the cooling water flow to process tubes fed by the crossheader. The reactor would be scrammed by one or more of multiple pressure monitor trips. The flow of cooling water through most of the process tubes fed by the crossheader would be very low and would be insufficient to cool the fuel elements in the post-scram transient. Coolant boiling would rapidly develop, and the resulting volume expansion would expel liquid water from the process tubes leaving many of the fuel elements in a steam atmosphere. The transfer of heat from the fuel elements to the steam would be poor, and fuel element temperatures would rapidly rise. Before the small amount of cooling available could affect a transition from film-boiling to single-phase cooling, a substantial portion of the fuel elements would have reached the melting temperature. In the worst case, the fuel elements in the major portion of two rows of process tubes would be affected. Heat transfer calculations indicate that uranium fuel melting may occur in the higher power fuel elements two hours after cooling is interpreted, if the reactor is promptly shut down. Any power excursion initiated with the loss of coolant to two rows of process channels would be mild.

[redacted]

The numbers of fuel elements subject to melting and the fission product inventories are nearly identical for the E-Q and natural uranium reactor loadings. The effect of the higher heat generation rates in the E-Q case is offset by the fact that there are about 15 per cent less fuel elements served by the header. Thus, the fission products released to the environs following the accident would not be expected to be significantly different from those calculated for the natural uranium loadings[1].

Worst Conceivable Accident

The worst conceivable accident will remain the complete the permanent loss of coolant resulting in a full core meltdown. This accident is not considered a credible accident. It is instructive, nevertheless, to compare the probabilities and consequences in the E-Q and natural uranium loadings. In the E-Q reactor, the constraints on lattice and loading design and on reactor operation, which are enforced by speed-of-control requirements, will be met as they are now in the natural reactor loading. Consequently, the ability of the reactor safety rods (assisted by the Doppler shutdown effect) to terminate an excursion resulting from a sudden loss of coolant during reactor operation and prevent a violent release of fission products will be maintained. The inventory of fission products and the probability of their eventual release from the reactor are also not expected to change appreciably in the new loading. The nature and magnitude of the consequences of the worst credible accident in the E-Q reactor are, therefore, not expected to be any worse than in the present loading.

PLANNED DEVELOPMENT AND OPERATION

Initial Startup Procedure

Reactivity uncertainties with initial startup in the lead reactor will be minimized by experience with pilot loadings and the fact that the E-Q loading is not a large departure from previous loading arrangements. However, to further back up the calculations and the information received from pilot tests, certain precautions will be taken in the initial startup of the lead reactor. Most of these precautions will be relaxed for subsequent startups contingent upon agreement between observed results and theoretical calculations. The main features of the initial startup precautions are as follows:

1. Control and safety procedures will be based on the assumption that the reactor is one per cent $\Delta k/k$ more reactive than calculations indicate.

2. The withdrawal of safety rods will be at half the rate permitted for existing loads.

3. The subcritical neutron flux level will be monitored continuously during both the reactor loading and startup phases.

4. The initial rise to power will be no more than half the rate permitted for current loads.

 [redacted]

5. The maximum power level shall not exceed 80 per cent of the previous equilibrium power level until the short term reactivity transients (temperature and xenon) reach their steady-state values.

If the operating reactivity is greater than predicted, the control flexibility provided by the combined use of horizontal control rods and poison splines will assure that unexpected reactivity increases can be safely controlled. Since the transition from the cold, just-critical state to the maximum reactivity peak following startup is one requiring several hours, and is quite easily slowed down if necessary, there is no danger associated with running out of control during a startup. If the operating reactivity is grossly lower than predicted, it may be necessary to shut the reactor down and remove a portion of the thoria. However, such action will not represent any signficant change in the safety of the operation.

Tests

The pilot loadings of the E-Q are of sufficient size to indicate gross reactivity and heat balance effects. The current tests constitute 5 to 10 per cent of the reactor space in B Reactor and KE Reactor. The preliminary data from these tests indicate that the E-Q ratios determined from physics calculations are correct within the accuracy of the evaluations from the pilot loadings.

A horizontal rod calibration test will be performed at one reactor during the early stages of the E-Q program. The rods will be calibrated against a decaying xenon transient. This test will be nearly identical to those which have been performed previously and, thus, will provide a good basis for determining comparative rod strengths between the natural uranium and E-Q loadings.

Minor testing during initial operating periods with the E-Q loadings will be planned to provide more detailed information for determining such items as temperature coefficients, xenon transients, and spline worths.

Modified Procedures and Instrumentation

The modified procedures and uses of instrumentation which are designed to prevent and minimize the consequence of loading errors have already been discussed. A device, currently being developed for automatically limiting the number of safety rods which can be withdrawn simultaneously, is expected to be available for the initial E-Q loadings. This device will make the limitations on safety rod withdrawal, currently provided by procedural requirements, an automatic feature.

Management

The long term management of the E-Q Reactor will not be significantly changed from current practice. Initially, technical representatives will monitor the charging and operational phase of the loading. The Manufacturing and Research and Engineering Sections of the Irradiation Processing Department will jointly develop procedures for assuring safe operation, and wil provide for followup auditing to assure that operation is maintained within the specified requirements. The

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initial loading will be performed under a Process Improvement Transition Authorization which assures that the procedures for loading and operating have been scrutinized in detail and approved by both technical and manufacturing management.

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