PRNG - 93 PUERTO RICO NUCLEAR CENTER “The Problem of Xenon Buildup in Operating Reactors" Angel Sanchez del Rio and Aviva E. Gileadi January 1967 ---Page Break--- PRNC - 93 PUERTO RICO NUCLEAR CENTER “The Problem of Xenon Buildup in Operating Reactors" Angel Sanchez del Rio* and Aviva E. Gileadi January 1967 * submitted to the University of Puerto Rico at Mayaguez in partial fulfillment of the Requirements for the degree of Master in Science (Nuclear Engineering) Work performed at the Puerto Rico Nuclear Center, Mayaguez (NO, AT (40-1/-1839 FOR U.S. ATOMIC ENERGY COMMISSION ---Page Break--- UNIVERSITY OF PUERTO RICO College of Agriculture and Mechanic Arts Mayaguez, Puerto Rico ‘THE PROBLEM OF XENON BUILDUP IN OPERATING REACTORS by ANGEL SANCHEZ DEL RIO A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE NOVEMBER 1966 Ka Rising Lex 16/966 a aiats teealteee a Dts As A EE g ie Le Le L506. ite ---Page Break--- Abstract A computer program was written on the IEM-1620 to determine I-135 and Xe-135 concentrations and negative reactivities associated with the buildup of Xe-135 under various operating conditions of a nuclear reactor. The one velocity point reactor model was used. The program provides operating options for: (a) continuous operation, (b) eight hours a day, and (c) 16 hours a day. The results are presented graphically in such a way that negative reactivities due to Xe-135 buildup in operations of the same time pattern but various power levels can be compared. Negative reactivity values due to xenon buildup computed by the program for the PRNC research reactor agree with measured values within 16% of A. The problem of minimizing the after shutdown xenon peak with respect to the pattern of shutdown is treated using a method described by Ash. In this method, a finite number of flux changes are allowed prior to complete shutdown. The sequence of flux steps within a certain “control period” is determined in such a way that the resulting after shutdown xenon.

peak should be minimum. A computer program -— HOKE — has been written on the TEK-1620 computer to perform this optimization. Maintaining the after shutdown xenon peak, with the aid of the KINEE code has been carried out for a number of operating fluxes, control times and step sizes. The results are presented in tabular and graphical form, MINEL-computed flux values seem to be corroborated by results obtained by ---Page Break--- ‘other investigators using the Pontryagin Maximum Principle, ‘An important advantage of the MINK method is its versatility, which permits extension of its use to a rather broad class of optimization problems with only minor modifications, ---Page Break--- I wish to express my gratitude to the many persons who collaborated on this work, but especially to Dr. Mviva B. Gileai for suggesting the problem, for supervising the work, for her advice, help and continuous encouragement. I wish to thank Mr. Victor Davila, Director of the Computer Center, CAMA, for his instruction on processing methods and for his liberality in letting me use the computer during nights and weekends. Ms. Anne Esy's most valuable advice on preparing the HDiKt-program made it possible to fit the whole program into the available memory of the TEK-1620 computer. The assistance of the Reactor Division of the Puerto Rico Nuclear Center in the experimental verification of the PEBG program is highly appreciated. The generous sponsorship of the Puerto Rico Water Resources Authority — which made it possible for the writer of this thesis to complete his studies towards the Master's degree — is herewith gratefully acknowledged. ---Page Break---

with the Aid of PHEK ‘THE SOLUTION OF THE OPTIMUM SHUTDOWN PROBLEM... see Method of Solution MIME Code. Application of the Pre SUMMARY AND CONCLUSIONS TABLES 1 THROUGH 25. FIGURES 2 THROUGH 23. MINEX Method to Numerical Results Obtained with the Aid of the Optimisation cone wnn add a w as wv ---Page Break--- APPENDIX 1. flow chart and program Listing for PREX ~— a FORTRAN program, written for the IBM-1620 computer, to determine ‘the xenon-135 and iodine-135 number densities as a function of time, for arbitrary operating fluxes. +--+ ee ++ Flow chart of the PREM-program ss ee ese renee Listing of the PREX-program 6. ss eee ee ‘APPENDIX 2 Flow chart and program Listing for MINEX — a FORTRAN program, written for the IBM-1620 computer to minimize the after shutdown xenon peak as a function of the control flux pattern see ee ee eee eee Flow chart of the MINEX-program ss see eee eee Listing of the MINEX-program 6. eee ee eee eee APPENDIX 3 ‘the Fonyagin Maximum Principle and its application to ‘the problem of minimizing the after shutdown xenon peak Page ng 126 az us ---Page Break--- ‘Table ‘LIST OF TABLES Comparison of PRE computed and measured reactivity values in the Puerto Rico Nuclear Center Research Reactor ‘Thermal flux (¢), iodine number density (1), xenon number density (1) and negative reactivity due to xenon buildup vs. time under 1 megawatt steady state operation, and after shutdown sere t scree settee Thermal flux (¢), iodine number density (1), xenon number density (1) and negative reactivity due to xenon buildup vs. time under 2 megawatt steady state operation, ‘Thermal flux (¢), iodine number density (1), xenon number density (1) and negative reactivity due to xenon buildup vs. time under 5 megawatt steady state operation, Thermal flux (¢), iodine number density (I), xenon number density (X) and negative reactivity due to xenon ‘buildup vs. time under 1 megawatt 8 hours on — 16 hours off operation during a 5

day week and after terminal shutdown see ‘Thermal flux (4), iodine number density (1), xenon number density (x) and negative reactivity due to xenon buildup vs. time under 2 megawatt 8 hours on — 16 hours off operation during a 5 day week and after terminal shutdown see ‘Thermal flux (4), iodine number density (1), xenon number density (x) and negative reactivity due to xenon buildup vs. time under 5 megawatt 16 hours on — 8 hours off operation during a 5 day week and after terminal shutdown see ‘Thermal flux (4), iodine number density (1), xenon number density (x) and negative reactivity due to xenon buildup vs. time under 1 megawatt 16 hours on — 8 hours off operation during a 5 day week and after terminal ---Page Break--- ‘Table 9 2 vit Page ‘Thermal flux (4), iodine number density (1), xenon number density (1) and negative reactivity due to xenon buildup vs. time under 2 megawatt 16 hours on 8 hours off operation during a 5 day week, and after terminal shutdown Thermal flux (4), iodine number density (1), xenon number density (1) and negative reactivity due to xenon buildup vs. time under 5 megawatt 16 hours on — 8 hours off operation during a 5 day week and after terminal shutdown A summary of MINEI-runs: characteristic parameters and results of the problems solved with the MINEK code... 56 Iodine number density (1), xenon number density (1), control flux (¢) and negative reactivity due to xenon buildup vs. time under the following conditions: operating thermal flux = 1015 nV, b= 2 hours, it = 0.5 hour and max = 6! Iodine number density (1), xenon number density (1), control flux and negative reactivity due to xenon buildup vs. time under the following conditions: operating thermal flux = 7) D = k hours, Ot = 2 hours and max = Eyl Iodine number density (1), xenon number density (1), control flux and negative reactivity due to xenon buildup vs. time under the following conditions: operating thermal flux = 10 nV, b= 4 hours, at = 0.5 hour and max = 6 Iodine number density

(I), xenon number density (x), control flux and negative reactivity due to xenon buildup vs. time under the following conditions: operating thermal flux = 10^n, b = 2 hours, st = 0.5 hour and 6 Gm ---Page Break--- Table 1: Iodine number density (I), xenon number density (x), control flux and negative reactivity due to xenon buildup vs. time under the following conditions: operating thermal flux = 10^n, b = 4 hours, st = 1 hour and 6 Gm ---Page Break--- Iodine number density (I), xenon number density (x), control flux and negative reactivity due to xenon buildup vs. time under the following conditions: operating thermal flux = 10^n, b = 7 hours, st = 1 hour and 6 Gm Iodine number density (I), xenon number density (x), control flux and negative reactivity due to xenon buildup vs. time under the following conditions: operating thermal flux = 10^n, b = 8 hours, st = 1 hour and 6 Gm Iodine number density (I), xenon number density (x), control flux and negative reactivity due to xenon buildup vs. time under the following conditions: operating thermal flux = 10^n, b = 2 hours, st = 0.5 hour and 6 Gm Iodine number density (I), xenon number density (x), control flux and negative reactivity due to xenon buildup vs. time under the following conditions: operating thermal flux = 10^n, b = 4 hours, st = 0.5 hour and 6 Gm Iodine number density (I), xenon number density (x), control flux and negative reactivity due to xenon buildup vs. time under the following conditions: operating thermal flux = 10^n, b = 4 hours, st = 1 hour and 6 Gm Iodine number density (I), xenon number density (x), control flux and negative reactivity due to xenon buildup vs. time under the following conditions: operating thermal flux = 10^n, b = 6 hours, st = 1 hour and 6 Gm ---Page Break --- Table 5: Iodine number density (I), xenon number density (x), control flux and negative reactivity due to xenon buildup vs. time.

under the following conditions: operating ‘thermal flux = 10^nV, b= 7 hours, St = 1 hour and Omar 9 eee Iodine number density (I), xenon number density (x), control flux and negative reactivity due to xenon, buildup vs. time ‘the following conditions: operating ‘thermal flux = 10^15nV, b= 8 hours, St = 1 hour and SmBCO ee ee eee e et eee eee ee Iodine number density (I), xenon number density (1), control flux and negative reactivity due to xenon the buildup vs. time: ‘the following conditions: operating thermal flux = 10^8m, b= 6 hours, St = 1 hour and Ome 2G eee lee eee B Iodine number density (I), xenon number density (x), control flux and negative reactivity due to xenon buildup vs. time under the following conditions: operating thermal flux = 10^M%ny, t= 6 hours after termination of full power operation, At wl hours ¢ mags gos ere eee «Th seem ---Page Break--- Functions Figure Page Negative reactivity due to after shutdown xenon buildup for various operating {x00 eee ee B Comparison of PAEX-computed and measured negative reactivity due to xenon buildup in the Puerto Rico Nuclear Center Research Reactor vv ee ee eee ete te eee eee eT Negative reactivity due to xenon buildup versus operating time — continuous operation se seve eee eee ee Negative reactivity due to xenon buildup versus operating time wave shift operation ses tee eee cece eee TD Negative reactivity due to xenon buildup versus operating time =< two shift operation ss vere etc eee eee 80 Ratio of the optimized after shutdown xenon peak to this peak obtained with immediate shutdown for several different operating fluxes fort DAW ss ee ee ee ee BL Ratio of the optimized after shutdown xenon peak to the peak obtained with immediate shutdown for several different operating fluxes fort O.5 BOOP ee ee ee ee ee eo BF Ratio of the optimized after shutdown xenon peak to the peak obtained with immediate shutdown versus steady state operating flux, for several different control periods (b). « Mnmakt-optimized after shutdown xenon buildup 4s compared to the xenon

buildup following shutdown in a single step from, b= 2 hours, t= 0.5 control parameters: 0 hour, max + MINEK-optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step Control parameters: 0 = 10m, b = 4 hours, t ~ 1 hour, ---Page Break--- Figure MINEK-optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step Control parameters: 0 = 10%nv, b = 4 hours, At = 0.5 hour, pmax = 9 + + MMEL-optimized after shutdown xenon buildup to the xenon buildup following shutdown, in compared single step Control parameters: 0 = 10nv, b = 2 hours, At = 0.5, after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step control parameters: 0 = 10M, b = 4 hours, at = 1 hour, MINEX-optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step Control parameters: 0 = 10m, b = 7 hours, At = 1 hour, MINEX-optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step Control parameters: 0 = 10m, b = 6 hours, At = 1 hour, MINEX-optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step Control parameters: 0 = 10'5nv, b = 2 hours, St = 0.5 hour, MINEX-optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step Control parameters: 0 = 10nv, b = 4 hours, st = 0.5 hour, ---Page Break--- Figure MINEK-optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step Control parameters: 0 = 10'5nv, b = 4 hours, At = 1 hour, MINEX-optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step Control parameters: 0 = 10^5m, b = 6 hours, At = 1 hour.

« 1 hour, GME retested after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step control parameters: go = 10^5 nr, Da = 7 Hours, St = 1 hour, Pmt @ MINEX-optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step control parameters: go = 10^5 nr, b = 8 hours, Ot = 1 hour, optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step control parameters: go = 10^5 nr, b = 6 hour gmc 200: bt = 1 hour, MINEX-optimized xenon buildup for minimizing the xenon concentration six hours after completing full power operation. Flow chart of PRE-program see Flow chart of MIMDK-program see Page + 105 + 109 + 3 + g ---Page Break--- Production of Xenon Equations of Xenon Buildup 'The operation of thermal reactors is unavoidably accompanied by the production of various fission fragments. Among these fission fragments, xenon-135 has a special significance because of its enormous thermal absorption cross section (about 3 x 10^-3 barn). Due to this high thermal absorption cross section, xenon-135, unavoidably produced during operation, tends to shut down the reactor and, as will be seen later, leads to a number of problems closely related to the operability of the system. In order to gain some insight into these problems, one has to consider the mechanisms by which xenon-135 is produced in the operating core, as well as those by which it is removed from there. Some of the xenon-135 is produced directly in fission, but the major part, some 95%, is created as a decay product in the following radioactive chain: WIS PI, rel, cal 5. The mechanisms of removal are: radioactive decay and formation of x = neutron absorption (xenon burn out). Using the one velocity point reactor model, the dynamic equations describing the time behavior of xenon-135 and iodine-135 concentration are given as: ---Page Break--- Base»

Ve EO + APT - WHXO-a,x a) B= yry0 - a, - wo @) ware X te the number density of xenon-135. As the number density of iodine-135 Ty 4s the macroscopic fission cross section of the reactor under consideration Yq Ae the fractional yield of xenon-135 Yr 4g the fractional yield of iodine-135 Dx Ae the decay constant of xenon-135 Dr 4s the decay constant of iodine-235 Wo" 4s the microscopic absorption cross section of xenon-135 Yor 4s the microscopic cross section of iodine-135 to the neutron flux which, in the case of the one velocity point reactor model, is given as the function of time. To above system of differential equations determines X(t) and I(t) 4. 'the xenon and iodine number density as a function of time, provided that the time pattern of the flux, Q(t) and a set of initial conditions X(0) and I(0) are given 'The analytic expression of the general solution is given by: (See Ref, 12) ---Page Break--- 1 , 10) « eFaLiOdoly j25, (eng (0)elot4' de « 210] w xt) = MOM ro yrKa QE MMMerxe} — were Lt) = Ap GE OU 3) WOE) a Ay + TSO) m 'The negative reactivity associated with the presence of the xenon-135 is given by i « oe ware Y= EP Xt o = tof is called "the poisoning" and Z is a parameter given by Z= E/E Qo) Ig? of and EqM being the macroscopic absorption cross sections of ‘the poison, fuel and moderator respectively. The value of negative reactivity due to the presence of xenon-135 is an important piece of information for the reactor operator, since adequate amounts of excess reactivity to compensate for xenon poisoning have to be included in the ---Page Break--- reactivity inventory -- If the reactor is to be operated for any appreciable length of time, 1+, Equilibrium Xenon Poisoning If a reactor is operated for a long enough time at a constant power level (as 4s normally the case with power reactors), the xenon buildup reaches equilibrium i, 4 point when the rate of xenon production from direct fissioning and from the decay of iodine exactly matches the rate of destruction by decay and by neutron capture, This

value, the equilibrium xenon concentration, can be computed at once from equations (1) and (2) by noting (qa) (a2). But “equilibrium xenon poisoning" is a significant figure that has to be included into the inventory of the excess reactivity required for the continuous operation of the reactor. It can be seen from equation (12) that the equilibrium xenon poisoning depends upon the value of the constant operating flux; It increases as flux increases to a limiting value of Prag = 5 (a3). ---Page Break--- If the reactor has to be operated on a continuous time schedule, appropriate compensation in terms of excess reactivity has to be made in order to overcome equilibrium poisoning. Like, After Shutdown Xenon Buildup While the value of the equilibrium xenon poisoning is limited to 5f AK, the xenon buildup after shutdown may be one or more orders of magnitude greater — and the problems associated with overriding it may become very severe, if not unsurmountable. Shutting down the reactor, i.e., dropping its operating flux instantly from the constant operating value to essentially zero, causes a significant acceleration in xenon production due to the vanishing of the large flux dependent negative term Yo°Xt) in equation 1. Thus the xenon concentration begins to build up swiftly after shutdown, and it comes to a peak value where xenon production is exactly compensated by xenon decay. Since in the shutdown condition the iodine supply is not replenished, further decay of iodine into xenon reduces xenon production below xenon destruction, and a slow decay of xenon sets in that is completed within 40-50 hours after shutdown. The value of the after shutdown xenon peak is sensitively dependent upon the operating flux prior to shutdown. The value may be computed from equations (1) and (2) as Yeax = {To + (1- wddx) XoPRIe = {To + t Ro} (1-Dare) where Ij and are the terminal iodine and xenon number density, which can be computed from equations (22) and (22); so that Kyi is also dependent upon the operating flux.

Break--- prior to shutdown, a family of curves representing after shutdown xenon poisoning as a function of time for various operating fluxes (Fig. 1) gives an idea about the magnitude of negative reactivities involved. The fact that there are a number of high flux reactors operating at a flux level of 10^n and higher makes the optimization of the after shutdown xenon peak an actual problem. Scope: The numerical value of the negative reactivity due to the presence of xenon in the core is an important piece of data. It indicates the amount of excess reactivity that has to be included in the reactivity inventory in order to compensate for xenon buildup. For equilibrium conditions this value can be computed simply from equations (8) and (12); for time variable flux patterns one has to integrate equations (4) and (5). A computer program, MBL, to perform this integration has been written for the JEM-1620 computer, using the FORTRAN computer language. In an attempt to test the validity of these computations, a 52 hour long xenon buildup experiment was performed on the PRNC research reactor, and the measured negative reactivities due to xenon buildup were compared with the values computed with the aid of the PHEK program. The agreement is very satisfactory, the deviation being within x AK (Fig. 2) ---Page Break--- After the validity of the PRX program was thus tested, PREX was used to compute negative reactivities due to xenon buildup during operation and after shutdown, for a variety of operating schedules and power levels of practical interest. The second part of the work is devoted to the optimization of the after shutdown xenon peak. As stated in Section 1-c, the after shutdown xenon poisoning may reach several hundred dollars. Restarting such a reactor any time after shutdown may be very difficult — if not impossible. Loading the required amount of excess reactivity in the form of additional fuel may be unsafe or at least very disadvantageous from the point of view of neutron economy, cost, etc. In

In order to overcome the above described difficulties, it has been proposed by several authors to minimize the after shutdown xenon peak by allowing a certain time interval, called "control period", between the termination of full power operation and the time of complete shutdown. During this control period the flux should be varied in such a way that it should result in a minimized peak after complete shutdown. The problem then consists in optimizing the flux in the control period with the initial after shutdown peak as a performance index, i.e., determining the flux pattern during the prescribed control period in such a fashion that it should lead to a minimized xenon peak after complete shutdown. In an attempt to solve this problem, a FORTRAN program HINEX was written (Appendix 2) for the IEH-1620, using the basic principles described in a paper of Ash, Bellmann and Kaluba (Ref. 9). As will be seen further, HINEX not only furnishes a numerical solution to the minimizing of the after shutdown xenon peak, but with very slight modifications can also be used to solve a number of related problems such as minimizing the xenon poisoning at a given time after complete shutdown or minimizing the control period necessary to reach a certain given minimum peak, etc. Besides its flexibility and versatility, this solution has the advantage of supplying an actual optimal shutdown program, using not all too long computing times on the TBN-1620 — which is the only readily available computing facility for students or for PRIC staff. It is estimated that the running time of this program on an IHNW7090, or a similar size computer, would not exceed a few minutes.

2. SURVEY OF RELEVANT LITERATURE The problem of optimizing or at least reducing the after shutdown xenon peak by means of varying the preshutdown operating flux in a suitable manner has been the object of many investigations. In order to gain a better understanding of the background of our optimization solution, a brief survey of the relevant...

Literature is included herewith: Dal and Babb (See Ref. 4) proposed various time-varying shutdown methods to improve the after shutdown xenon situation — without obtaining an optimum solution. Rosetécay and Weaver (See Ref. 1) optimized the after shutdown xenon peak using the Pontryagin maximum principle. The Pontryagin maximum principle is outlined in Appendix 3 of this report. Since the Hamiltonian of the system contains the control flux as a linear variable, it follows that optimum control leading to the minimization of the after shutdown xenon peak consists of a number of switchings of the flux between zero and its maximum value, Qo. The type of control referred to is a pulsed control or "bang-bang" control. To determine the optimum number of switchings, the authors used a trial and error method. Kohes Sato (See Ref. 3) considered the problem of optimization of xenon buildup after shutdown as well as after power reduction, assuming that the power level after reduction will remain constant. His treatment is also based on the Pontryagin maximum principle. He obtained solutions for six problems, using the flux rate and the inversion period as control variables and the after shutdown xenon peak and a minimum xenon value at a given time as performance indices. The flux after reduction was kept steady in four cases; in the remaining two cases, flux reduction amounted to complete shutdown. In a later paper, Ash (See Ref. 12) presented a method to solve the minimization of xenon poisoning at a given time using the method of dynamic programming. The results of his computations — carried out on a Philco 2000 computer with an ALTAC code called DINPROG — verify the results obtained with the Pontryagin maximum principle, namely, that the optimal flux pattern for a minimum after shutdown xenon peak consists of pulses of "bang-bang" control. An empirical formula correlating the magnitude of the control period to the magnitude of the after shutdown xenon peak is given. In this paper (See Ref. 12), Ash

points out that dynamical programming and the Pontryagin maximum principle are complementary methods of investigating optimally controlled processes. The DINPROG program is described in detail in a report of Ash (See Ref. 16). ---Page Break--- 3. PREX, A DIGITAL METHOD TO COMPUTE NEGATIVE REACTIVITIES DUE TO XENON BUILDUP UNDER GIVEN OPERATING CONDITIONS 3+a, Mathematical Model of the PREX Code Numerical integration of equations (1) and (2), furnishing the iodine and xenon concentration as functions of time, were performed with the aid of the PREX code, written in the FORTRAN language for the IBM-1620 computer. In order to make the problems amenable to digital solution, a suitably small time interval Δt is chosen and the differential equations (1) and (2) are converted into difference equations as follows: Δr = [¥,E¢ - NT - WLOlar as] Δx 0 [Δded «eZ - Δx - WE xolar a6] ‘The number densities at time t+Δt are determined as: X(te + Δt) = X(t) + Δr a) X(t + Δt) = X(t) + Δx a) Using this step-by-step approximation PREX permits evaluating the values of the iodine and xenon number densities as well as the negative reactivities associated with xenon-135 as functions of time, for any given reactor configuration and for a given set of initial conditions X(0) — T(0). The flow diagram of PREX as well as a listing of the program ---Page Break--- are given in Appendix 1 of this paper. (See also Ref. 10.) Results. Comparison with the Experiment As mentioned before, the validity and the accuracy of calculations performed with the aid of PREX were tested against experimental data. The testing experiment was performed at the Puerto Rico Nuclear Center Research Reactor with the participation of the 1964 Advanced Reactor Laboratory Class under the supervision of Dr. A. Gileads. Reactivities in this experiment were measured with the aid of a calibrated regulating rod. The regulating rod was calibrated with the stable period method immediately before the performance of the 52-hour long experiment. No changes were made in the core.

configuration after the calibration was completed. At the beginning of the experiment the ore was xenon-free. After the control rod had been calibrated, the reactor was brought to high power, about 1 MW, and was put in automatic mode. The red positions were recorded at regular time intervals and with the aid of the calibration curve the reactivity changes were evaluated and plotted. After 42 hours of high power operation the reactor was shut down and immediately after that brought to a very low power level of about 30 watts. This power level, being several orders of magnitude smaller than the operating power, corresponds to zero power from the point of view of xenon-135 production or burn out. The buildup of the after shutdown xenon peak was observed and followed through several hours after the peak was reached. Simultaneously the xenon-135-caused negative reactivities were computed with the aid of the PHEX code using parameters appropriate to the materials composition of the Puerto Rico Nuclear Center Research Reactor. Measured and PHEX-computed values are compared in Table 1 and represented graphically in Figure 2. As can be seen from the table, as well as from the diagram, the agreement is within 1% or ± 5. It may be concluded from here, then, that the PHEX-computed values of the negative reactivities due to xenon buildup can be reasonably trusted, and that PHEX-computed values have a good enough accuracy to determine xenon caused reactivity requirements to be included into the reactivity inventory of a reactor. This establishes the value of PHEX as a design tool. Xe. Xenon Associated Reactivity Requirements in Various Operating Modes Computed with the Aid of PHEX. PHEX was used to determine xenon associated reactivity requirements under various operating modes. The operating modes considered were chosen with actual operating schedules and power levels in mind, including: 1. Steady-state operation, at 1 MW; 2. Steady-state operation, at 2 MW; 3. Steady-state operation, at 5 MW; 4. Pulse-shift.

operation, at 116! 5. One-shift operation, at 218 6, One-shift operation, at 514 7. Two-shift operation, at 101 ---Page Break--- Two-shift operation, at 220 9. Two-shift operation, at 5 HW. Negative reactivity due to Xe-135 buildup, as a function of operating time, under the above mentioned operating conditions, is presented graphically in such a way that negative reactivity up in operations of the same type, but at various power levels, can be compared. (See Figures 3 through 5). Tables 2 through 10 contain the computed concentrations of I-135 and Xe-135, as well as the negative reactivity due to the buildup of Xe-135. The xenon concentrations are given at each hour, but the computation is carried out with $\Delta t = 5$ min, due to xenon buildup in order to minimize the error due to replacing differential equations with difference equations. From the above diagrams and data one can see that the negative reactivity due to the xenon buildup will remain well under 33A/; only if the power level does not exceed two megawatts. For five-megawatt operation a reactivity allowance of about 5fAX/y has to be made, ---Page Break--- as 4» THE SOLUTION OF THE OPTIMAL SHUTDOWN PROBLEM: 2. Method of Solution The problem of minimizing the after shutdown xenon peak is treated in this report with the aid of the concepts developed by Ash, Hellmann, and Kaaba. (See Ref. 9) First, the problem is reformulated in a somewhat more explicit manner, as follows: It is assumed that a high flux reactor is operated for a long enough time, so that xenon and iodine are present in equilibrium concentration (given by equations 4 and 5). At a certain time it is decided to shut down the reactor. However, instead of shutting it down by reducing the value of flux from to zero in one step, a certain time interval, the control period b, is allowed between termination of the operation and complete shutdown and in this control period the flux will be varied in such a way as to result in a minimum xenon peak after complete shutdown. The problem is to

Determine the flux as a function of time in the control period in such a way that the after shutdown xenon peak—which is obviously dependent upon the operating history in the control period—should be minimized with respect to the choice of Q(t) in b. In order to determine the optimal flux pattern in the control period, let us note that the magnitude (and also time of occurrence) of the after shutdown xenon peak is determined by Xp, Ip, the terminal values of xenon and iodine number densities at the moment of complete shutdown. Further, the values of Xp and Ip are determined by the flux pattern in the control period, b, and by the initial values Xo, Io, and (Jo; in other words, Sue = Hoax Cte Tp) Kaa = Fuax” X£(%0, 10, 00); 210%, 26, Qo) the after shutdown xenon peak value Tyge is a function of the flux pattern in the control period, b. Our purpose is to determine O(t) in such a way that it should minimize X,,*. This we shall do by using an approximation that makes our method amenable for digital computation. To achieve this, we shall divide the time interval b into m subintervals each At long, so that n is defined and then we shall determine the value of Q(t) in each of these subintervals, considering (Xt) constant in each subinterval. This step digitalizes the problem: instead of having to determine Q(t) in b, it suffices to determine Oy, Qpeseen a set of constant values in each At time interval. By making At small enough, the sequence thus determined will approximate the optimal O(t). Besides the parameters b, At, @, Xp, and Ip, the value of Lug is dependent upon the choice of the sequence; therefore, to achieve this choice at the set Oy, Qyeeve, one can calculate the stable values by using the PEEK computer state described in Chapter 3 of this paper. On this, the problem of finding the optimal sequence is reduced to the following steps: On a, deliberate all the possible choices of set Oye Oe under a given @, At, Qo.

Te each adatattte set of, Qevee Qa ealente fase CO, Opes Qa) uotng the FRE code. x dnorg all ras thus ealeulated,chowe the anaest. tre Q, @, On set Leading to tds minimal Xyyy valve Ss the optinal flue pattern we wero sooking. Step (ay th press of emartine al} tho aatastte sete of, On can be significantly simplified by observing that since the Wanittenian of the aysten contains the control flux at the first desree only, the optinal flux pattern —- according to the Pontryasin Kaxtmus Principle —- can only take on one of two values: sero and pay — a mecimm values 4, 0, the optinizing flix pattern consists of a svitehine back and forth between O and Qage The valve of Qnax miY de equal to the operating flux Qo or, in certain cases, may be grester than Qo. ‘aio type of control is referred to as pulse control, or “bans-bang” control, Since in each subinterval there are only two adatentble choles of the flux value, nanely, 0 and Q,.,» tho total muber of sdnisstble acts is 2", n being the number of subintervals. Thus our method of op- ‘imization can be further reduced to the following step a, Enumerate all. adais Ga - 2 tn mnber, te chotces of the set 4, b. Uekng the RRB code compte Xgagy Pertatnin to the flest adadaeibie choice of Qyasss On and store. ‘cs Repeat step (b), with the next admissible choice, compare ---Page Break--- the two values of Tag discard the bigger, store the alien of the two, also store the pertaining @,, 0, see On sete ds Repeat step (¢) — ttl all the adaisaible choices are aed vp and the Last set of Qyee++ Qn stored ts the required optinizing flux pattern, with a given b, At and ho. A computer code — KINEX — that will execute the above outlined optim zation has been weitton in FORTRAN on the 15-1620, The program listing and the flow chart are given in Appendix 2. Ub, uerical Results Obtained with the the optinization caleulations using the MINEE code were performed on the TEA1620 computer at the Yayaguer campus of the University of Puerto Rico for a lange mmber of cases, The operating fluxeo

wied varied from 3.10% av to 104 nv, control periods ran from .5 hour to 8 hours, sizes of the subintervals varied between .5 hour and 1 hour. In certain problems, the control flux was raised to twice as high as the steady operating flux, under the assumption that operating the reactor at this higher power level will not be a safety hazard and continued for a short time interval only. Our results indicate that using 2 Qo instead of 0 (for naz) does not improve optimization results significantly. Characteristics of the problems solved with the aid of the KINEE code, together with the resulting control flux sequences, are presented in Table 11. ---Page Break--- Figure 6 shows the ratio of the optimized after shutdown xenon peak to the untreated xenon peak vs the magnitude of the control interval b for various fluxes. As can be seen, the results improve as the operating flux increases; with a 1 hour control interval we get a peak reduction of 0.00% at 3 x 10^19 mux but sit with a 10^15 sux. The subinterval At = 1 hour, Figure 7 shows the same values for At = .5 hour. Figure 8 shows P(b)/P(0) vs. control periods only; this family of curves also shows a very definite increase in operating flux, for various proven in optimization with the increase of the operating flux as well as with the increase of control time. Figures 9 through 22 show the diagrams of MINK optimized after shutdown xenon buildups compared to the xenon buildup for the same operating flux following a shutdown in a single step. The optimizing control flux pattern is also included here. Application of the LINX Method to other Optimization Problems It can be shown that with very slight modifications the LINX method can be applied to perform other optimizations besides the minimization of the after shutdown xenon peak, described in the previous sections. Optimization problems that can be solved with the LINX method include the so-called xenon minimum and the xenon time optimal problem. The xenon ---Page Break--- minimum probes can be formatted as

follows: A reactor 2 operated at rated power level for a long enough time to permit the development of equilibrium xenon concentration. It is decided to shut down the reactor, allowing a certain given control ported by. The xenon minimum protein consists in determining the control flux pattern in the control period that will lead to a minimum xenon concentration at a given time T>b. Using the same argument as in section ina, Page 17, the optimal control pattern will be of the "bang-bang" type and the steps of optimization will be the following: a. Enumerate all admissible choices of the control flux set Pr Ops On, altogether 2 in number. Using the PREX code compute X(T) pertaining to the first admissible set and store. c. Repeat step (b) with the next admissible choice, compare the two values of X(T), discard the bigger, store the smaller of the two and also store the pertaining in 2 save On set. d. Repeat step (c) until all the admissible choices are used up and the last set of choices is stored as the required optimizing flux pattern for a given b, At and Qo. As can be seen, the only modification consists in using X(T) instead of Yuax #9 as a performance index. A sample problem for minimizing X(2) with the above described modification of MIMEK has been run for an operating fix of Gon 104 nr, bw i hours and Ta 6 hours, and the optimization results in a reduction of xenon-caused negative reactivity to 52% of its ---Page Break--- unoptimized value. The detailed results of this run are included in Table 12 and represented in graphical form in Figure 23. The optimal xenon problem consists in determining the minimal control time necessary to reduce the after shutdown xenon peak below a given value. The solution of this problem requires the following modification: a. In a KINGX problem with b=0 and compare the resulting after shutdown xenon peak lya with the given value of the problem. If Xmax is smaller than the given value, we have the solution; If not, go to step b. Increase ty At and repeat.

step a. The required minimal b ie the first b which will lead to a smaller after shutdown xenon peak than the value specified in the problem. The problem has not been run on the Ts-1620 because it would require too much time; however, it can be run with no difficulty on a bigger and quicker computer e.g. the IS7090 or TBATOPA. ---Page Break--- 5. SUMMARY AND CONCLUSIONS Sa. A computer code -- PUK -- has been written for the Tii-1620 in the FORTRAN Language that will furnish numerical values of xenon-135 and iodine-135 material densities, and of negative reactivities tied up in xenon-135 for any given operating flux and schedule. Sb. PREX has been used to compute xenon-235 associated reactivities in the Puerto Rico Nuclear Center Research Reactor for several actual operating modes and power levels, thus determining reactivity requirements for 1, 2 and 5 megawatt operations in 1, 2 and 3 shifts. Among other things, it has been determined that the present fuel loading in the PRNC Research Reactor is insufficient for 5 megawatt operation. 5c. The validity and accuracy of PREX has been checked against measured values in the PAC Research Reactor, and the agreement has been found to be within 3% of Ak/g for the case considered. Sd. A computer code MINEX has been written for the TiiM-1620 in the FORTRAN Language to perform the optimization of the after shutdown xenon peak. This computer code is very versatile and flexible and with minor modifications it can also achieve the xenon minimum and the time optimal xenon profile. A further advantage of this method consists in the fact that its output supplies the actual operating data for the control flux program leading to the prescribed value of the performance index. ---Page Break--- 5-0. After running a large number of MINEX problems, it can be concluded that the optimization of the after shutdown xenon peak leads to increasingly better results as the operating flux and the control period increase (See Figures 6, 7 and 8). However, the increase of the control flux

fringe to 2 Qo does not seem to affect the Iggy values significantly (See Figure 22). ---Page Break--- ‘TABLE 1. COMPARISON OF PRE-COMPUTED AND MEASURED REACTIVITY VALUES IN ‘THE PUERTO RICO NUCLEAR CENTER RESEARCH REACTOR ax ax t é x ee couPureD —weatuneo 2.00 .3u4ss7asee13———_.39107s03n013 wore 06 2:00 ‘Socssrageeia ——Taovaaeoseeze ‘oto ‘ote 3.00 Shuissnusini = “igveareereele cons ‘oes 00 Sauussiaseena

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“a7g2u776ee10 3eioseisees a3 Tae 87°00 Targ2u7760¢10 ‘Beasarsaeeas 1.380 Ties 48:00 larsaur76eei0 [aearenrens 3391 3469 49:00 Targau776er10 1362397758015 1302 1462 50:00 Var9217768410 “s7e65a3ee15 1366 aasz 31.00 ‘47921776210 asun7sa0ee5 2.338 1.420 52.00 479217768410 ‘aaszoaTeseis 11308 1397 ---Page Break--- 26 TABLE 2, THERMAL FLUX (CD), IODINE NUMBER DENSITY (1), XENON NUMBER DENSITY (X) AND NEGATIVE REACTIVITY DUE TO XENON BUILDUP VS. ‘TIME UNDER 1 MEGAWATT STEADY STATE OPERATION, AND AFTER SHUT- 1 x AK/« Enea ot aussie seeraeerents Rosorzea93ER15 SStsasrniens sipeemicas Reon pihdessrasents inereaysests croneaens ‘nosessesn tenis Sslovvoseaty sarasgeezSERls Shiececesets saseetesaveass cabeoianseats NOTE: The f sign in the above data should be read as a+ sign ---Page Break--- XENON BUILDUP, L R3tSsbehoeas sae seems ieee isaTTSONERIS rite sirisuinasees Resrszesenis Rsazocrazenis SSasorsisents x a% cigseevazeeot Ssetse=co miadntzoewe=eo itosenaaeeee Brareotrsteneo <8 tw, STEADY OPERATION. 8885833: 8992929993983 ---Page Break--- TABLE 3. THERMAL FLUX (()), IODINE NUMBER DENSITY (I), XENON NUMBER DENSITY (X) AND NEGATIVE REACTIVITY DUE TO XENON BUILDUP VS. ‘TIME CORR 2 MEGAWATT STEADY STATE OPERATION, AND AFTER SHUTDOWN 1 x e ERGiSas SRRY ERRRES Eltmiens fcinnice e siaizeezenco Rigsesecsatnis Sciesvesveceel Ectsagescstaet ---Page Break--- XENON BUILDUP, 2 MW, STEADY OPERATION. x aN t o ecooccv00E=9e Faasecs7szeeis Seooceceoe-sy Aisovcsvaients 3 Rilecsatenaet 3 eeisieadlcee si eoesesectt0 Eek isco ssiiceneeces a Msvocceccems K.tossesseete sasoriesssemis izcseininec: Eh ---Page Break--- TABLE 4. THERMAL FLUX (()), IODINE NUMBER DENSITY (1), XENON NUMBER DENSITY (X) AND NEGATIVE REACTIVITY DUE TO XENON BUILDUP VS. ‘TIME UNDER 5 MEGAWATT STEADY STATE OPERATION, AND AFTER SHUTDOWN t o 1 x : ER Lae Eeeauee Siistarnizenis, sizpzoezsetale mcaSecensbeats Tiisoeatemta fcaesestzeened ---Page Break--- XENON BUILDUP, 5 MW, STEADY OPERATION. Pacer caesest Persatc ---Page Break--- TABLE 5. THERMAL FLUX (>), IODINE NUMBER DENSITY”

(1), TENON NUMBER [DENSITY (1) AND NEGATIVE REACTIVITY DUE TO XENON BUILDUP

V3, ‘TIME UNDER 2 MEGAWATT @ HOURS ON — 16 HOURS OFF OPERATION DURING A 5 DAY WEEK AND AFTER TERMINAL SHUTDOWN x 8.591000 te TSHEEHG ERS 20708767600 Seseei ase EUG Ezosessorens Scdecestecesi> netrssceeni ---Page Break--- 2B XENON BUILDUP, 1 MW, 8 HRS. ON-16 HRS. OFF. 1 x cee Scateszaszens scisazessnenns B nani Ehlannssnete siatintiesteas seosee ---Page Break--- XENON BUILDUP, MW, 8 HRS. ON-16 HRS. OFF. t o I x Ny, EdGhaonels scishesseets slecnsient =e Pidesesziaums ecvouoseoet=eo ES mrsesen Bilsee Reocecoooemes | 22h 3005 Be Eutrransoenis Shajsrabtenis Sounizzasens 3 Wigs ---Page Break--- XENON BUILDUP, MW, 8 HRS. ON> 16 HRS. OFF. caeageenat—eh cetoseeate-el csrrreease=el caausasoae=el saie=t Trsovemls RSHTYAzWe=ed 3% ---Page Break--- 36 ‘TABLE 6, THERMAL FLUX ((), IODINE NUMBER DENSITY (1), XENON NUMBER DENSITY (X) AND NEGATIVE REACTIVITY DUE TO XENON BUILDUP VS. ‘TIME UNDER 2 MEGAWATT HOURS ON — 16 HOURS OFF OPERATION ‘DURING A 5 DAY WEEK AND AFTER TERMINAL SHUTDOWN 9 I x Setaeragpaenns netazreazzeny 2 t shusesennems zerzoeznenis on nerssiyzzsenor RO 3382238828883 obsasrsosens ---Page Break--- XENON BUILDUP, 2 MW, 8HRS. ON-16 HRS. OFF o srggneor seems x scznreeser a3 Einniaat aK Rae oe aetisseponeaot ---Page Break--- t ¢ L x epasaanay qe sirainiease Rastenl-00 HRS. OFF 38 ---Page Break--- 9 XENON BUILDUP, 2 MW, 8 HRS. ON-16 HRS, OFF. t > I x any, ---Page Break--- 40 TABLE 7, THERMAL FLUX (()), IODINE NUMBER DENSITY (1), XENON NUMBER DENSITY (X) AND NEGATIVE REACTIVITY DUE TO XENON BUILDUP VS. ‘TIME UNDER 5 MEGAWATT 6 HOURS ON — 16 HOURS OFF OPERATION DURING A 5 DAY WEEK AND AFTER TERMINAL SHUTDOWN saa: iota Een Sime EERERG Llssnnat EiSEiean Someest SidostroseMis RciSeTSOLzEROt Rivestessnemis Razoesarzecnen ---Page Break--- XENON BUILDUP, 5 MW, @ HRS, ON-16 HRS. OFF. I x Ye nasrestaneceas Reesoe77z2¢R15 8.29777689. ne miganazsasens Ripe Bisons: 42 Sitzetessormot 323 1isoeeesente Scasseisioemis jOEMLS ReAOOOOLYIEALS citrosseenls Sibeszseeenat 3S

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---Page Break--- 4 XENON BUILOUP, 2 MW, 16 HRS, ON-8 HRS. OFF. 1 Reszononnaenns Reipeatiniems x coer mitetdenes Rgisboreieas etreeasents ‘igaaesizaens 3 Ber een arrest Rctesissocenot Rezozess3scn01 RHisseresenor

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---Page Break--- TABLE 12 A SUMMARY OF MINEX-RUNS: CHARACTERISTIC PARAMETERS AND RESULTS OF THE PROBLEMS SOLVED 56 ---Page Break--- 37 2ire eee o | | 1 | 0 jo) o 1) oto} ipl Si 6 iofoto ot, ore wna xm omar SRSLSNVEES SUSIWAL IEW ---Page Break--- 38 tSunro 35K |yro90" ao anu wad |u| ---Page Break--- ” i SOI t ae) > a 80 emu zane | aye a Sea cue xm #7 eyrud sarge vagy foe ao pee ae amie) ure [Canxanias sewino mrmatad] row 49] (ap -wlBI0 So Nel pONa mya] xOuG] 46 esEMAN fszuNIEns|roMUNCD| MUSEO ‘s11ns38 tL ‘SUBLSWVEYE —DUSIESIDVEVHO (1809) SNA XZNIW 30 ANWWANS ---Page Break--- TABLE 12. 2 a2 Bh 3 a 2 38: “7 a 8: 30 50 30. 50 oo 50 ‘60 50 oo 50 oo 50 ‘ou 38250 +92 3: +10) +o. 150 zt +3 Ae +15. 6: a7 “18, 9 #20: 421, #22. +23: 2h: 425. 428. 60 50 do 50, 50 50 50 50 50 50 50 50 50. 50 50 50 50. 50 50 60 TODINE MUGER DENSITY (1), XENON NUMBER DENSITY (Xx), CONTROL FLUX (>) AND NEGATIVE REACTIVITY DUE 7 XENON Buildup VS. “IMG UNDER THE FOLLOWING CONDITIONS: OPERATING THERMAL FLUX 2109 ar, bo 2 HOURS, Dt = 0.5 HOUR AND Oman = De 9 +.39000000£+15 128467670816 7227013809516 71 S6763E+1 6 +. 25090 S65E+1 5 21257 5727691 3 1233204 5961.6 #1221293066+16 20908994E-15 992641 5E=15 B30B623E+16 311794281 5-16 4¥117026335E=16 +1151 5667 5-16 3115331 3TE=1 6 1145183396416 a1 3805248E=15 [131001 08E +16 12430987E+1 5 117960446416 11193 532E+1 6 10079261416 307 SR065E+15 [BL 7263216915 73509566413 66 2534376+15 S671 7E+1 5 15372 7495E91 5 1483791 156915 2435631406415 Ba 3 2 2 2 2 1 1 a 1 32172 5E+1 5 80557 SE+1 5 8539447641 5

5788495615 3221 347E41 5 10909 7H9E+1 5 8628250E+15 6953 977EH1 5 52662726415 3748573E+15 P29RGOGE+16 1 +-79000000E +1 § #1023%, 58608 +1 5 193 3SNEHI S +187UQSSIZEH1§ $1828 189LE91 § 19355051 6E=1§ #1102793026-15 111215308915 [11 B863862E+15 12530990616 SBT IB 7ENS SITG6LSBLBESTS aH 114051986616 442328 5-16 HA735096E+15 5114991 966E +16 HL1SEOBTSZE+1S eT EBS7BDESS Saphy sei 6 5551212816 552047641 5 6997226416 S266 OBE +1 6 353054415 50964208416 T72WUGErN S 39462 5E+1 6 STUB TEI 6 5224296+16 OWBGE TENS 5547366416

05203KE+1 6 5462 76E+15 0395106416 5362 SE +15 0039590E+16 #19 S52045uE=15 +1907 56434815 TBo12012 7415 181624129641 5 HT P2TTOBUEVS, 3086 37 6E+1 $ a 4 1 a 1 a) n nH a 1 1 uv a MY 1 vA x +.00900000E-99 +T000G0°00E-39 "30900000 +15 +"3o0002006 +15 ‘20000008 -35, + LOGeD0BD0E. >io0000000E +To000009¢5-39 +! 000956006 -39 {000000008 -39 $:99000,906-33 + 9G000000E: = rogoo00006 -99 +160000000 -36 +!o00000008-59 000000008 -35 + Loo0000008-99 ooooo00e=33 000000008 -33 +100000000E -$9 +!o0000000€-99 +1o00000006-99 *Too0000008-39 locoqg00=99 = + L0b000000E-99 +100000000E-39 +Souoo00u0€-85 +!00000000E-39 ouuw000e-39 +7000060008=39~ *ovouy000E-39 -r“00000000£-39 +ovovov00E-39 + Tovocovo0€-39 + 100000000 -38 Tovau0000E=85 Tooouova0e-99 ToooD000E=35 00000008 -99 ovvv9000E-993 Sovowvo00e-99 TouadD000E -95 ---Page Break--- a ‘TABLE 19, IODINE MUMBER DENSITY (1), TENON NUMBER DENSITY (x), CONTROL PLIK AND NEGATIVE REACTIVITY DUB TO XENON BUILOUP VS. TDM ‘UNDER THE FOLLOWING CONDITIONS: OPERATING THERMAL FLUX = 203nv, b= 4 HOURS, At 21 HOUR AND Oya, =o t 6 30000000 +16, 2701 3609E+16 11325450315 H2UB71TQKEST S 253034 53E=15 2283862 SE+15 FrROS65125E+15 situbr faut + S5E*1G Souucesects Tae ae 6 NT 00” #11217 SEH 412,00. ¥,109822 57E+16 13200” +1987100866+15 _ A100 5188883343615 15,00 +,30035771E415 WO2E+1 S FATi00 + UBSnS2BETS HB L004 50434320601 5 419200 +, 52617400E+15, —#20100__ +14737952 76415 421,00 -r. 426630656415 422.00 _+138i4161096+15 423,00 +.34591924E+15 #2i200 131184236415 00 + 280477 12E+1 5 00 +1252 555668+15 427200 +122 741 557E+15 #28200 1204777208 +1 429200 +,18439239E-15 80.00. +.156036826+15 431.00 +. 14950BK0E-15 32,00 4113462 5496015 1 +-70000000E+1 5 53468354641 5 11237755416 pasoyaaients 50; + Hronétogdee $ 113352226116 124665775+16 133202716415 1393599 66+16 +614683039E+16 +614655038E+16 +a 1402837 HE +15. 133087896416 HE tal] 525398516 104962 7E+16, +10572150E +1 719098798E+16 +962 65919E +15, +e QUOMIZ51E 41S re B2L1AU4BE$1 5 =82703347E+15 14 3hi61 BEN 6 x +.00000000E-99 +Looool000E-33 +¥1300000006+14

+23 00000008414 +100090000€-95 +! 00000000E-39 +100000000E-39 +locsao00vE-99 +,0u0v00008-99 +Tov0000008-35 _+} 90900000- 99 *¥Lo0o00000E-99 #790000900E-39 “*,00000000E-39 +oowou0098-39 +000000008-39 L00000000£-99 +200000000E-99 +100000000E~89 +o0000000E-39 1000000008 -99, +200000000€-99 +200000000E-39. +2¢u000000E-39 ¥100000000E-39 +1000000008-99 +19c000000E-93 +109090000E-99 +100000000E-39 +100000000E-93 4.7311 96328415” +, 09000000E-99) $4782 7429 06415 +. 70274052E+15 }.ooc00a008-39 +100000000E -39 ---Page Break--- 62 ‘TABLE 14, IODINE NUMBER DENSITY (I), XENON NUMER DENSITY (Xx), CONTROL 50 #1200 31150 12568 +2150 #3100 33.50 +h260 +5.50 48 48.00" 28 +9.00 #13200 +100 +15,00 416.00 +1700 #18200 #19200 420700 #21200, 922.00 423.09 +2400 425.00 426.00 727200 328.00 429200 +30-00 $31.00 +3200 FLIK AND NEGATIVE REACTIVITY DUE TO XENON BUILDUP VS, TIME ‘UNDER THE FOLLOWING CONDITIONS: OPERATING THERMAL FLUX = 103ar, b= b HOURS, At = 0.5 HOUR AND One, = Do I x 4 oe ~ §.3000000082 15 ~=.7000D000E=15° +, D00CDDGE=99 42.423

TREN pezoes15 +182 245sH0E~15 +.00000U00E~99 +2850 TpFongsODETS SL93KSEISWET§ +100000000E~-95 +3235 Beroeelé,=.103452522<18 + 10v0000008-99.__ +3. . 3 BES suger 2.119377 856716 © =:CO000000E-39 +3889 T2308 2056-14 =112031800E-16 1Z0000000E+i# he 1 6h £123426035E-16 +.10691332E+16 +.3 00000008414 3.700 T123752u30E+15 +19547521Er1 5 -30000900E+1 3.39 eather aeen16 “18e37% 5896-18 +lo0000000-99 ~ +3.059 2122833126615 <9 70774G6EH15_ = 993.360 _ SHRP G ST IuBMUOTET5 + -0DOO00COE-36 45-29 "203601 756-16 ~:11174035E-15 8 Higgrootiens lry7hzes7e—15 sh 07 TIVBSLSbB7Er1G rs 1231 GRIEG 9 T4263 TEPBbpBBMESI 8 4112 750998E+18 | +100000000E-99 ~ +42 Tbe osiierG 221316090515 _~L00900000E-99 +4. $62 FIV SEI 9OSOESTS —. TSS2121 SE+T S ~~. COCO ION: FIVBoviOSzE+16 .1 38052 76-15 FI UAAM3ZNETTS + VOLOTELESTG TUsrs7ooestG +114220166Er1 +.00COOLUVE~39 4.925 LU 2r6geBE016 +1145723398-15 +L00C00000E-99 +4974 TRIPIZI9ENG =L1uK76TAZETIS +. 0Od00000E-99 +5. s QgUUESTG +. 1% Sle61 TET +. 000000008 7110959622616 +

:14570974E41 +: 0000L000E-99 $210399835E+16 “+114502662E+16 +.000000008-99 lagengpotecis =r1u3uh4I2E+18 _ +. 09900000! "B32 3603E415 +114340955E+16 ARIE BRU soovo000E-39 37037087 641 5° ¥.13750733E15 | +.000060008-99 GT SoU TESTS "4.1 303K902E+16 | +.00000000E~99 qrebeséanzer1 § 211 30%0218E=15 +Lo009000NE-39 SMBgI TOMES siagoLsauesle +. cogaegade 32 TIBLBRSENLS | +11217012E-16 +, 09000008 -38 TihowpaziZes1$ =111709529Ee16 _+.00002000E-99 ar3onUgTStEs15” .T1233H28E+15 “¥.000000008-99 pani pieces “+.10766240E+16 "+.09000000E-39 T1255503301 § =l10292538E+15 | +:00000000E-35 212680870915 1962235818415. +, 00000000E-99 7123959910E1§ +193 595220615 +100000000E-95 T2siganess Lleadsz901€-18 =so0000008 -99 ETM ptooe SBusassa3E+15- SL00D000E= TH WSsposen § +160258945E+15 +. 00000000639 Fiv5p51hageH1 & +175063827E+1§ +.00000000E-99 “1h4937928e15 +1720091998+15 +. 000000008 -99 SH277IBAGES 3 +:68101314E415 +-00000000E-39 39 sOUSCOOE-B8 ---Page Break--- 8 TABLE 15, IODINE MIMGER DENSITY (1), XEVON MOMBER DENSITY (2), CONMRL FLAK AND NEGATIVE REACTIVITY QUE 70 XENON BUTLD- UP VS, TIME UNDER THE FOLLOWING CONDITIONS: OPERATING THEWAL FLUX 2 10Mnv, b = 2 HOURS, Ot = 0.5 HOUR AND aux = O° t 1 x +00 +.9858B95NEF16 +7971 3394E+15 “Dis0~ F19357030uE IE” 1125940356416 41100. $1888072006+16 +:16794770E+16 FTiis0-F 1aN2E HEHEHE —“+.20501 ISVESTS 32100 _+1850552766+16 +113 7892008416 ~-FIBOTZ SOZSERTG FLT T5207 556415 35100 =176616373416 +.20897802+16 31500 F171 6297-16 +2 39KHNOTERTE TH2G0 TLE OLNTSIENTG +.2568351 56415 i550 ¥1ESSO1G39E=16 ~ $129136208E-T6 $5100 416216 7302E+16 = 131322 5926416 $8550~ $2 890027B2E+1G6 “332614 7IETS 28200 1 35m931HE 16 +1349705206+16 TBis0° $1 83iwA7STEMTE F.56656203E-16 T7160 +1 5032 55+16 577603126415 SE cATBTSp00ECIe <-3an79IB7ErI 9 3B100_ F1U5u36K53E016 +139024576E+16 35150" HUSTZ5NGZE+TS “+. WOGLSZOTESTS 49100 +140930211E+16 _+241257330E+1 6 33150 ¥1388K6705E+16 ~=1417679 50E+1 6 410.00 +:368692 596+16 +242155072E+1 6 10150 Ti3u992NPSELTG +.424303K4E.15 W100 +1332112296+16 + 42601 191E+15 HTH. 50

FST SZOBSSESTS +.42675030E+T5 +.00000000E=39- +412150 1203932996015 | +2257423 56416 313580 °-¥125576250E+16~ +.u2taoeT oE=16 $14 $0 +123038662E-16 +241 5473396-16 215280 +120752065E-16 +.4071 75636415 16,50 _+11B5936 S316 +.35730977E+16 FAT. 56 FA GBITZSEHTG + SCOT IUGUESTS 418130 +11 51GHN37E16 | $137412073E615 419.50 4.7 3663493E+15” >.361332 558415 720250 +:12307370E116 +.34BOLOSHESTS 420250 F11V0BS7HOEKG +133442382E+15 150 998678606215 +.320634398+16 $2358.89 SIZTHEFTS

+130500038E-15 424250 +181033831E+15 ~129302903E+16 325.80 +172993923E+15 =127940973E~15 426.50 165751700E+15 ~126601 579E+15, $2725) ri s92200K7E+1§ +!25290682E+15 F820 s13}astousenLs 9.3001 30676-19 529.80 +.lBOSU2B0E+1§ =.22772430816 430.50 =.43230103E+15 +.21 571 78BE+15 431130 +139995023E-15 +1201 3097-16 4 +.00000000E-99 +1000000008-98 1000000006 -93 Me 42.759 i359 -5.813 SL19000000E#1S 47.131 +Lo0000000E-98 ¥:00000O00E=35 louovos00§ 39) + 00000000 -89 ‘0000000035 }o0000nE-38 ‘ovavooc0E-$9 TB 7.233 362288 391236 ¥16.085 102842 Sg TT TS =Tooo000008. +200900000E-39 ~ FTOOOIOOOOE=95 + L0uggu000E-35, ${00000000E-33 +ovovoov0E-39 +200000000E-39 +.60000000E.~99' +Ton00u0008-39 Floucoveo0e-98 ‘000000006 -35 (OGODGUOE=95" 100 00O0E-99 ‘90000500E-99 ‘90000000E~35 ‘000000E-39 {000000008 -33 S00OUGOO0E=S +Log000000! +Lo00000008 +1oudn00008 99 +oovogs00€ 59 +!0009000 + 100a00000E = +ooo00000E-99 Too000000E-39 E99 8 12.10% 4125622, =13:072 H130457 213.785, T0535 — 3182281 oT 457 $140 552 214.607 14.746, 2182736 7107800 “sts. — $11,098 210,61 — ---Page Break--- 64 ‘TABLE 16, IODINE NUMBER DENSITY (I), KENON NUMBER DENSITY (1x), CONTROL FU AND NEGATIVE REACTIVITY OWE TO ZENON SUTLOUP VS. 16 WER TH FOLLOVING CONDITIONS; OPERATING THEGMAL FLUX = allay, b= h HOURS, Dt 21 HOUR AND Ogg = Oo 1 x any 00UE-99 2.7592 GO90E-99 +5.81 34 wOQOUUUE 99813221 ros +9850 54E916 =.7971 339415 a¥ito TERB8o72 808-16 +:157987708-16 2100 =L79BBBN GEG “i 2NOW2ZBOESI 6 etd Tegzesaepert6 +!29212908116 <1 0000000E +15 «10.3972 OD TLAPROSUSETTS. “c120H979HE+1S +

.U.0V0000E-99 4-184 Gpappogoe ys IRAN SENS issue gs Ef Fae CeE Tg T125AzINg7EN§ =louovCKOUE-9g <B-1100 TE esorsyeriG =12750956KE-15 =. GOUOUOLUE-93 9. 5223 TLRSEIDRIESTE =130718250E-16 + .0UULLOULE~39 -10. 6330 TIAZgS7es1 6 3133175 94KE+18 + .0000U00E-99 +11. 4837 TigsouatTTerte T3agh8E77Er16 “Lovvv0v0E-99 12.1112 3135981 008Er16 +_362N9G72Ee16 +.0v0U0000E-99 Than rirosertg "<370075E=16 +. UUUUsLLE-39 RUSTE NS 3TSRRTTE La -ouosuedtess zizeagepnhest e SIBpMghZs1Es16 /OUUGDE-B9 Bsebghdgen1s 6 .372HN3NE1S + -vLUOOLOIE~39 TIDT Bag 1BER LS LZ IZBAIE TE +s vvvouace TYgRB19SUEV 16 =.35196271E+15 > oveuu0dE Ty patyeaieel =.Z3z6KB72ETS ~LoveLoLOUE Tia Bonga 7E+16 23h 3904GE-1 -.gOvOLLOLE Tiabongn7SE“16 =1334TU5NGETS OUGDEE~ [112636857616 +1323239W9E-16 -.CuUOvO0UE. TIM398940E1§ —.Z117613KE+16 = -0U000000E-29 Tilogshaares1s =229952183E-16 -.beveuvede 33 Tigzso06Z1E-1§ +128706595E+15 ~:OLEDbBOVE 9g 3185323010E-15 127571660615 ~:00000U00E-99 SIT5OS5VUNER1S 1263 57698E 1 5 22676091 82EC1§ +125153325E-15 | ~-ov000000E~59 Tieogoi226E+13 123465662615 0uvuuonDE-95 SISMBSANITESTS =1228005456+15 -0vv00000E-99 B3NT SNIQES1S. +2 1662680Er16 +. CUOUODODE-99 “hast ZOUSET8 -.2055579E1$ + OULOO0LIE 99 Troog6egiE-1s 1 gSzpOge-19 r-ouguovede 29 Tigeniuadiesy $ -.184458316-16 +. vov09000E~-39 Baloo 213253005118 91 7HWGK73Er16 _ +, UOUOVOLDE-99 ---Page Break--- 65 ‘TABLE 17, IODINE MUMBER DENSITY (1), KENOW MIMBER DENSITY (2), ‘CONTROL FLUX AND NEGATIVE REACTIVITY DUE TO XENOW BUILD UP VS, TDS UNDER THE FOLLOWING CONDITIONS: OPERATING THEOL FLIX 2 104ny, Yaax = 2 t L +98 5889 54E=15 bao 72 T3891 16E1 5 591 7E*16 nga 57ae-15 218266842 76-15. 157303701 E15 518822 7E16 i549 Si SES 18 35936~15 377200526015 A1ZLuv__ #13390 W8 E16 13.00 +1306) 29756165 siklou #12757 56700+16 312W3397276-15, SEBMBBENG THI 635h22 96615 #110731 639-15 2132700366018 42220u FL1T953N SHES 323.00 | 1107674326415 £296 991 9598-15 $187 3007226-15 si 7b700Rb2EH § +2 7091S O5E%1 5 Si Ggugnaae tS S752 24u2E~1 5 215181 52 556-15 56733061 5 sazons726-1 5 378720736 +15 1B SNES

323072982 76-15 27600935615 x = e 797033 96641 5 7987 70E+15 1 wi22B0E-1 4 [23921290816 34 5107 5E~16 2:52 36-1 1072 S04E=16 136 52 326-16 eG 31h 38E AS 21907 5506-15 L2UT4ERSLE-TS = 12593U8K0E+16 TIZBSTAGUNENTG #1297347 78E+1 8 T30KGN77E-1 6 130897537615 #13101 Su22E1 6 2 130ugdbs0Es1s TBosb2472E-16 = 130057629E-16 *129i 3701 E16 1285975726415 127872 SBKE-16. 12696211 515 1 260U33 9861 6 "125071 1626 +18 226077973818 #1230 74KSiE+16 22068 SPOEW1 6 "12 V0708u7E+18 2200843708 18 T1911 5361E 16 116167915615, SINJRAS32 IE 5 £163 50167615 115481 3026715 SVi6Ag3UDE HTS thy OLE Te 33008E-99 Toesr000C08 -83 Taudsusgue~y9 sTro000008 +15 aligOUUOGE 99) P20000098 89 + luuuscou0e -93, Tucu00008-33 ‘ouuvde~99 Tuccuuuane 93 yOUGDDUE-39 (oududdoUE~95 OGUUBUE 93 FloueuboOUe 99 Tu00U0L00E 38 +ouuoUdovE-93 TuubuouudE-35 uyocoso0E~39 = {uu000L00E-98 4 os00UCLUE-99 #i0yudud0VE~99 “TUgD004U0E-99 wbOULE-~BS JOU E-95 J:00U00E~33 TOS000UGNE 39 Tivu0 0006-39 Lavooou0ve-99, “onuuooe 39 ‘Ov OUDGUOE Patras a se nononue 33 +Tocuusno0e-9g +7 vO00000E-39 be 7 HOURS, At = 2 HOUR AND “Ye “2.7592 #526134 18.3221 39.3572 “VSB 13.2521 lait 4 798 +6. 3408 #75032 825650 313288, ign “19.2926 410.9535 219.6331 710.7360 71016926, #10.5791 410.6078 #1021895 9.9336 9.6480 49.3336 3.2143 +8 26783 O13 345 ---Page Break--- ‘TABLE 18, LODINE MUMBER DENSITY (I), ‘XENON NUMBER DENSITY (X), CONTROL FLUX AND NEGATIVE REACTIVITY DUG TO XENON BUILD- ‘UP VS, ‘TIME UNDER THE FOLLOWING CONDITIONS: OPERATING THERWAL FLUC 2 10U4ny, bx 6 HOURS, At = 2 HOUR AND nex = 2 t I x Bere ee 290E+15 299212! a SRahB seri 6 +:362.04 5236416 271072 304E+1 6 1431039926416 1409421 0E+16_ SEY BoBI e=1 +.212B861 236416 Sz ahoe17 6016 22573672 16-1 TAREBIE 4128162793641 Sdbpsitabests S29 o7atyerts +.29161876E+16 21389962 70818 28Rubgo0ENS 161909696E+16 sr gahgas7ucete S6B427E+16 74428 S2E+1 6 ae SagGrTeer te B41 SBE~16 Ziplo0. 2 Sucauyyse-18 $1300 +.311932226+16 21800 +1280983 50€=16 Sloss oshoes 6 _ 416.00 412279933261 ~ 17,00 “+, 205372 796 +16 #18.00_ +, 18493664E-16 713-09 "E.veGeng

Lobet "-26ouba60br1 __#20100_+71 50108 65E+1 6 '507208 421.00 +.13521 560416 ~-27531630Er15 322200 +11278001BEr16 +1261 5579816 10 FIT0971SHZEX16 +.26023730E+16 $19BB303S2ET 725174302619 Slbg0RK726E+1 $= 12K2b292KE+16 The 8 srovaigueests:1239629G3s16 se ee iperls dghesiTiei6 228.00. +. 6506i629E=15.+.214002S1E+1 6 7300 #10,00, +11 200 429.00 +. 58612 7HOE+15 +. 20536 2 7E+16 —# sete 7 28Ee 3 a 1gep9sh eel e +3100 “+. 7 apaON Tse + 6752006 +1 6 eee +33.00 +3! pad 2 389E+1 6 ee 437.00 +.; 25071 S7ECIS + HBAS ¢ -pagnn9ane 99 ‘ovo000UE~ +, yy0000008 FLuv0v0000E-$9 +f ooayago0e-99 +1090000001 Stoovoouo0e=99 14,2171 STrooo0000E+1 5 414.9203 310000000E-99._=l.8706 ‘10D000000E-99° +6.2 598 Q0000000E-39.. +7-3681 +oo0000008-39 ° +8:2h04 *La0qu0u09E-38 +8-9094 To00000008-39 +9.4036 2a oQq00Q06=38._ 19.7488, 100000000E~99 +9:9660 “‘Jougv0u90E 99-10-0756 +1 000000008 39° +10.0943 - +=, O00900006-93 +10,0379, ‘J0000000E-59 \vaQVOOYE~99._+9+ Fu 00000004 7915300 {O00U000VE~99 +9.2821 sT000u0000E-33 +3.0080 +T0u900000€-39 ++100000000E-39 200gBo0008-39 ‘=: 00000000E -99 “Tovoo0u008-33 +6:4643 99, tbbgoo008 "38° 33:2582 +r0p000000E-39. ~4.9766 ‘ovooo000E-33° +4.7072 ---Page Break--- ‘TABLE 19. JODNE MOGER VEASITY (7), XENON NUMBER DENSITE (1), ‘CONTROL FLUE AND NEGATIVE REACTIVITY DUS TO XENON BUTLD- ‘UP VS, ‘TIMG UNDER THE FOLLOWING CONDITIONS: OPERATING THBOUL FU 2 105ny, b= 2 HOURS, At = 0.5 HOUR AND Snax * 0 1 x +. 98UB2476E*1 7 1 gRNS93R SE 4188711 363E+16 #18419 5602E+17 718496004517 +.83872872E+15 3110171 683E+17 *114219909E+17 SAB Isgeaee ts 4176537793E+17 +-87368367E+16 $2 689039706417 +11 5449378E+17 2103 9806s 17 +:

20300193E~17 3959418766417 +.2530138KE+17 $520391 S1BE+17 1267901 66E+17 Slas3ardsiess 7 +.315030336+17 $NGGBG234E+17 +.33537630E17 136831453617 sBeaiy SUT PENT —*.5595806 55717 FI2QBBSHSREHI 7 +.36502944E+17 126920302617 +.36694137E+17 7 +13658861 08-17 1B43492E+17 +.362360068-17 4135679 592E+17 +3%956990E+17 3730100023E+17 Bissaeel7 1331392078017 Bese? 7132096700817 gaguaErT7 | 7.30993099E217 T6INES

7 3290490176417 “seat acest d 5292455416 76830021E15 99207201 +16 62 34069KE+15, 12 7490920E+17 +126301625E+17 1251182606417 3125948398E+17 2227982726417 HID YG7ZGUZESVT $1205764526+17 FI19S11976E+17 B01 9328217 7488086 E+17 $2055651 S5E+16 FINTOWNSHZE+1 6 +136972073E+16 +.1 3133303456416 3.1 +7572 08552 E+15 ~ 867701 3E+17— ax, 9 * +-090000006-99 03 $:00000000E=33 + duoyoo006-99 235.209, + Toooooa0ess 43-221 Trbopoo000E-99 "27553 1000000006239 30: 200000096-99 53:4 ooBoeoaeE=33- 278-366 pong 90008 59 27580 Troog00000-33 +99:870, $1090000006-99 +109.047 +260000000E-99° +116.089 $,00000000E-99 +121 .132 {OOO00OO0E-89 4124-468 $7000000006-39 +1 ovovo000E-33 +1 To0000000E-39 +126.650 S00000000E-39 +125.430 3100000000E-93 +123.504 F!0000G000E=35°+121 « 19 +118.039 Ebooooooooe=95-11 Tas 71 + loovoo00vE-99 +111.102 +200000000E-39 +107°285 (QVO0UOOUE-39._+103.321 “ODDOOOODE=99~ +99-264 +00000000E-99 _+35.159_ +1 00000000E-39 ~ +91-082 +100000000E-99_+86.946 Froavo00d0e-39 +82.896 300 3 +[00000000E=35— aa é +L00000000£-99 00000000 -35, *.900000008-99 }.00000000E-99 ---Page Break--- ‘TABLE 20, IODINE NUMBER DENSITY (1), XENON NUMBER DENSITY (x), CONTROL, FLUX AND NECATIVE REACTIVITY DUE TO XENON BUILD~ UP VS. TMG UNDER THE FOLLOWING CONDIEIONS: OPRRATING aolSnv, b 24 HOURS, At = 0.5 HOUR AND THEOL FLUC = Ona = Oo 1 500. +, 98482476617, 150" +19 346932 5E+17 41100 +.88711363E+17 1550 -n.B41 956026417 Oo +27 9909712E17 150 +1 75061992617 BG Sct ge ag 7e7 #3230 ts aa 1205617 G0. + 6xBg8ORGEHT7 +5200" +1 629630346417 +6,00. +, 56716060E+17 oo +151 0088 90E+17 0+ h6020034E +17 9200 261 SWO9SE TT 419,00 +137341170E+17 F1T.00 +.3363631 76417 H12l00 +1302 90516417 413200 +127292898E+17 _—kioo _+12h5850026+17 15:00 +1221457796+17 416,00. #21 9948555617 417,00 +,4 73693 568-17 18.00 "$.181865216+17 419200 +114 580570E+17 #20200. ¥113133956E+17 21209 +.1 18308 76617 222200 +,10657079E+17 423.00 ,95997334E+15 ~ #2h.00 “4.86472 730E 15 425.00 +17 78932 WHE 16, #28200 +1701 64938E+16, 27.00 +. 532031 1E+1 6 423.00 +. $5932 5B5E+15

#29200 +1512839308+15 ¥30.00. +1h6195719E+16 431100 HN 6IZ3K3E+16. 132.00. +13 74837208 +16 133.00" #33764 7296-16 up #130814 72NE+16 SB8ioo” H27337090E 8 x +,030728726615 = 572086526 +18 2101716836017 ny a 2 421.9908E+17 7892 5B6E+17 421512 5617 421 14ORE+1 7 6503855E+17 09H) 5E=1 5 2460751 E+) 3 2724059E+17 7207033€+17 08256286 +17 "12 3699004E17 "12 5926566E+17 7127599 504E +17 4128797163617 129589226417 7130035820617 4130193 S20E+17 +;30106173E+17 +2981 56126017 +4293 5742.66 +17 *128762 SS7E17 1260573406417 71272 664B 06-17 526408470617 +.2550101 7617 2655001 7EH17 1235341 DE+17 $122546420617 +12163982 66417 120665123617 71197035N5E=17 11875721 5E+17 A 7BBB0T ENN 7 +1159291256+17 21605529 7617 oh 315205803617 1163600996417 o +.900000008-99 00000000E-39 +,00000000E~39 *200000000E-99 +5090000008-33 ‘ooo00000E-39, [00000000E-99 10000000 +16 d0009000E-99 ‘10000000E-$3 +00000000E-33 +T00000000E-33 +190000000E-39 +Tooo000008-39 +00000000E-39 +200000000E-39 +Louo00000E-39 +loouo00008-33 +2000000008-39 +1000000008-85 +Lo00000008-33 AK 42.903 +19:802 425.082 “hie: Ou 4591561 721091 4821033

93:538 +95. +99. 680 #1021422 41032971 1062 514 Showi2i1 ++260000000£-99° +103.206 + .00000000E -99 :00000000E-99 ++100000000E-33 +2000000006-39 +,00000000E-99 00000000E-93 +,00000000€=39 00000000E-33 +200000000E-99 ,00000000E-99 +1o00000008-39 +Tovoo00008-39 +S000000008-39 +!000000008 -39 +, 0OU00000E~39 r:0vov0000E~99 =100000000E-33 Fova000008-33 +104 620 +99. 561 #972121 U2 362 91st? 88.371 285,009 281°671 $782253 ---Page Break--- ‘TABLE 22, IODINE WMGER DENSITY (1), XENON NUMEER DENSITY (x), t 00 42.00 "3-00 —.+hi00 5.00 +6.00 47.00 ~ 39 iso —+12100_+ 413-00) kio0 +1500 415200 417-00 — #1800 +19,00 420,00 421-00 422.00 +2300 —#2h 200. 427.00 #28200. #29200 —#3.0.00 #31200 432.00, 733.00 $300 435.00 +36..00_. #37200 + 90N0247 65°17 +,.83872472E+15 +,09000000E-99.._ 41,00 +, 80711363017 +101 COMMREL, FLEX AND NEOATIVE REACTIVITY DUE TO XENON BUILD. [UP V5, TIME UNDER THE FOLLOWING CORDITIONS: OPERATING THERMAL FLUX = 10nv, b= 6

HOURS, At = 1 HOUR AND Snax 0 I x 6 16836 +17 +.00000000E-99 925HKE+17 +.00000000E-99 8 017) $,79909712E+17 “4.178 Buaituage17 + .0000008-39 333, HOM BIE $1G4D39594EH17 +.2931356UE17 +.0000000E-95 423840603 56+17 41333627668+17 +110000000E+1 S62K7I230E+17 +254561208+15 +200000000E-99 Sr 5BTBOWDENT + Se6uB7s¥E-VC = -cu0Un0ODE- 35 BUE+17 +.11361637E+17 +.00000000E-89 fSososciert? sctsscporsest7 +/a00000008-$9 SUNTSORSTENT) tr1deotPstest} . z:oCoo000E- 39 HBTOWDKOLETT F.2117ESELE*17 =.00000000E-39 SBBTISMMESLZ <2 1240635617 + -pogugn9ue $3 +2300823808-17 +!2ho5: 47 -149000000€-99 H2go7sT08e-A} L25750733eN 7 =\o0u0ov0NE- 9 124392 968E+17 3125439121617 =!ovco0000E~39 #121972 7982517 146039612217 + !s00o0000E-39 SIQ7S27S1E17 ¥.2o9Bo070E+17 +199000900E-99 $1178290036017 1 26}02401E 37 v ood909Ge-99 =11608008' H2CMMSO7KE=17 =! C0000000E-33 sliigeseze 17 +1 NoORODUGE-99 413031 369F-17 5 Lau 300006 -93 S111736465E17 +.28073003E417 +, v0v0u000E-99 110573830417 +1243069088+17 + !CO0UUOUDE-39 1952h7523:+16 +123599417E+17 +. yvoguugve-99 +85797373E-16 2278605417 +, c0u00000E-99 ST72bAG MEG «219467206417 +! v0000000E-38 G61 Sba7Ee16 <.21OU4aR E17 =-00000000E-99 LG27097HRE+16 +1202120BKE=17 +.00000000E-99 BuGzbene Tligaseuséect) “oouvvovNe 3B +150803365E+16 +118460343E+17 _ +l0v000000E-38 SRSOSIGIEES§ <1 768i giE+17 +" o0u0g000E- 98 $UT207322 E16 > S51E+17 +.20000000E-89 SIS71Q09N7EIE + ‘oo0v0000E-39 Bee Sosa +1335009966+16 =15126939E+17 +; 00000000E-99 HBO 7A55E+16 +116346278E+17 +!ov000000E-99, +:271930366+16 90000000E-93 SI2MRGOSBEHT +.12858205E-17 +100000008-99 ---Page Break--- n ‘ABLE 23, IODINE MIMEER UBGITY (1), KEWN MIMBER DENSITY (1) cove, FLUX AND RECATIVE REACTIVITY DIE 70 XENON BUILD ‘Up WS. TID UNORR THE FOLLOWING CONDITIONS: OPERATING TMEOAL PLUK 2 10S, b= 7 HOURS, At = 1 HOUR AND ane #0 t I x 9 ed +.00 #.98482476E+17 +,83872872E+15 +.v0000000E-99 +2903 21500. $18B711363E+17 110171583417 +.00000000E~33 2100 +179909712E-17 +117092 SBBE+17 #3100 5191981337617 1242} 1h02e +17 TUICO FeOMBS9SGNENIT +12931350UE+17

+.) $5.00 +158406435E+17 +133392766E-17 +.00000000E~-99 36100 4152611552417 +:3650330SE+17 +11 00000006 +16 F7loo. F1s72svktgee17 2503190476415 | +100000000E-99 8200 +251571129E+17 +.59276369E18 +-000000008-99 fanaa salenesuizzeen7 =. 104130376417 +-09009000E-38 F10200 +241045302E+17 + :14087406E+17 +: 00000000E-99 H1L00 ¥137693636E+17 +117052568E+17 +,00000000E-99 312.00 +133953016E+17 +119405663E+17 +;00000000E-99 #13100. +130585048E+17 +121230585E+17 +, 00000000E-99 Hglo0 +127550516E+17 +1226012108+17 +:00000000E-99 7 A1§L00_+2248170656+17.

+123582513E+17_ +. 00000000E-39 $16,090 +12235NS11EH17 +22423158SE+17 +: 00000000E~99 317.00. +1203 36860E+17 +124596501E+17 +:00000000E-99 HAlo0 +118130970E+17 | +124727111E417 +,00000000E-39 319100. +116339301E+17+124555831E+17 +: 00000000E-39 Y2ol00 S2147181 908-17 +!244180R3E+17 +1 00000000E-99 421200. $1132579226+17 _ +:24043020E+17. + 00000000E-33 i SIVigi2 s42E+17 112355590417 +100000000E-99 +.10757668E+17 +.2297B HOE +17 }OO0DOU0E-39 SibapaghaGEN6 °122330983E-17 +1000000008 ~ +.B7289003E+15 1625381E+17 +.00000000E-! 7862847 6E+16 OBB 52 S9E+17 +. VOOOOD00E-99 _+1J0827224E+16. +.20113673E+17 _+.00000000E-39 .+69.623 6379998BE+16G +,19323684E+17 }0000000E-99 +66.839 Sphaso7ieris +110526608E+17 +L00000000E-98 64.122 1 768002E+16 +.17723181E+17_ +.00000000E-99 +61 .348 4G6317G3E+16 +.169257S4E+17 OO0OVQ00E=99 +58. 588 TH2005126E+16 +116137431Er17 +:00000000E-93 +55.859 F3p0_+°37837 296016. 1-1 59240217 _+-YOQ00000E-39._+53.176 +3200 +. 340830206416 +11 7 Sooooo000€-39 +50: 551 335l00._+130701799E+16 +113855228E+17 -L00000U00E-95 | +47.994 736,00 +,27655085E+16 +113147933Er17 ,00000U00E-99 +45. 511 437.00 +,2h9tT50fE+16 =112453843E+17 +. 00000000E-99 +43. 708 438. ST7BWIUIEH7 +100000000E-33 +40:790 0 122k 01 S5E+16 ---Page Break--- cs TABLE 24. IODINE MIMGER DENSITY (1), XENON MUMGEER DESITY (x), “13.00 sthtoo 15.00 +1620 +1 7,00 200 319200 20.00 #21200 22:00 +2300 28,00 25.10 28.0 +2700 428100 329.00 +30. 31. 32) 333.00 Bison, $35.00 238.00 $37.00 43800 +3920 (CONTROL

FLUX AND NEGATIVE REACTIVITY DUE TO XENON BUILD-UP VS. TIME UNDER THE FOLLOWING CONDITIONS: OPERATING THERMAL PLUG eax 20° I 98h M247 66-17 #108701353E917 ¥279909792E+17 #271961 3376917 hi 39594617 053517 Suggest? 4739161791 cee b HTB B7IIEH17 2426392326017 =. 38400722601 7 *1345276536-17 WB 11652 736-17 1280731 756-17 2125287666717 #122 7783036+17 212051263617 211949309317 Shy 669283617 wi Vago 7ND ENT HIV 35Q90UHE=17 +ii2igortye-17 4110961 7556-17 #196701 33315 Pi BagNlgg3E TS +1601 201 636-18 HLTBITOIORE 6 316501 0349615 #1 5836024hE-15 FL 52 7501 O1E=15 IATSHSH20E 5 T1280201 16-15 <1gS5S34NE-15 +15930030E+15 13 12bb3E-15 12818034 56-16 Ti253auho8E+15 4122865870615 31205972 18E15 x =.838 728726415 *110N71 5636417 6117892 5988+17 Talay Vhoze-17 +12931 3568 E+17 33362766E-17 =136503305E +17 1336622706417 sThoug77bveH § 71 Sly 3996E+1 5 956235316416 ri1293292 06017 S11 55543776417 S217 14D50E+17 9388417 2074684BE-17 el2n5u7h27Es17 =122243070E+1 7 ©: 22579734417 122697636017 122632162617 2241 385uE+17 "12208051 SEAT 21622012617 2109271 5-17 204978656417 +1198 5291 0E+1 7 HI1gIJO76NEsI 7 #11 8652h93E417 NT a 73731717 POI30 EN? hie281h6e17 15536211EH17 VaR 2 59617 Wert f9 SE=17 T13hOS13KE 17 1272691KE+17 312058 $036°17 2111631 390E+17 110816673617 13ne, b= 8 HOURS, At = 2 HOURS AND 4 ~.000000008-99 +1a90000008 -98 +Tovado0008-39 +Tovo00u008 -99, 71000000008 -39 +1000000008-99 600000008 -99 99) +lovu0cco0E-99 =18-843 OOOODE~99 ~33.099 aovg000E-99 --hke.767 sTov000L00E~55 + 54.187 sroopouguve- 39 +61.663 Tovovva0ve = +67 °%50 FiGuuvgvO0E~99 +71 2814 GOOLO00VE-99 +74.932 +T00000000E-39 | +75.993 + l0u000000E-99 +78:159 Tlecoouco0g-33 278567 *rouUO00VE=38 + 78.340 +Tevoo00008- + oeaoooooe. +Tooooucooe. +S oga0000vE-35 + Leuguv00ve -99 pU000000E 99 + Luu0uOU0VE=33 +Touan0u90E-99 +ougu0000€-99 +ooo00000E-39 +Toopeuuoue-99, «UGUOLODOE-4 sGOV00E-9 1990000008 -5 +lovooog00e~-39 +7 0000000E-99 “Loua00000€-39 =100000000E-39 STovuoo000E-39 337.441 ---Page Break--- D ‘TABLE 25, IODING NUMBER DENSITY (1), XENON NUMBER DENSITY

(x), 10200 #11200 A2Zi00 ato sihico0 +1820 416200 sHzo0 ABiL0 ATO #20.0 221208 222.00

»23.00 (CONTROL FLUX AND NEGATIVE REACTIVITY DUE TO XENON BUILD-UP VS. TIME UNDER THE FOLLOWING CONDITIONS: OPERATING THERMAL FLUX = 10nv, b = 6 HOURS, At = 1 HOUR AND eax = 20 1 x 4 4% EhOLNTGENT +.03072972EH15 +.» 09009%E-99 42.903 STTISOSEST] HAOIMNSHIENT FLO OE-99 «35.205 ST9GODTIRES 7 c17OS2SKGEH] Flucyvyn0E-99 +6t.934 2haithogee7 °.90009000E-99 483.007 293135GE17 be U0UUvE-99 +101.466, 340543 SE 17 333627S6E+17 +. 20000000E+16 +115.43% .]23307S4E+17 +.33485600E +15 +.U0U00U00E-99 +1159 GST SISIGE+T7 +. 7209957115. 2 10G0C OOGOE-99 +24.957 1 5B6099NUEHI7 +112099598E+17 +. 0u0,0000E~99 +44, 651 +, 52365933E-17 =.17550072E+17 ~.00000000E-39 +60.776 +7621 662E+17 21321694E+17 3 +73. 604 +! 3 BOSBIZE+17 = +. 2431077 SEr17 99 +64.151 G4OZHGE+17 +. 126031 303E+17 9 +92.184 o Sn03gS3e-17 ~120375930E~ 17 +,Q0000000E-39 98.226 1313553066017 =129529619E-17 +10 0U000UE-59 +102. 562 2020275917 +. 30K51S20E+17 +. NOUVNE99 +105.442 2 564062 3E +17 30936266E+17 +. VODU0UOVE-99 +107.U85 229165) 3E+17 3110904 7E+17 +. GD000000E--95 +107. £33 doesent? “ahbedSeded? Lio couonoe 5 =. V959473 5E+17 +. 30735981E+17 +, 000 99 SLANE? #.30271318E*17 = ,0.00U000E-99 S.T50NG005E17 +.29653502E+17 0000500E-59 #13591 ONSET e2ROU1 SURE? +. 00000000E-99 ~ T2225 HET 2BAZSUSTE +17 OROOME-39 a0 Tapghgdbye) scovvo0e-39 >, 2S3TWSSVE+17 9 +. C0006U00E -99 25345043E+17 +, 00000009E-35. 24352055E+17 +. 0G090000E-95 23346731E+17 +, 0UUU0UUE-SS 22330365E+17 +. 00000000E-39 313317806717 Tiocuosuv9E-99 5 Tlosooenene-38 7 stunvsuuaue-99, 17 +, O0OD0NNGE--95 7 QUQUVGE~33_ 7 OG NIGE-95 “V7 uGGUUGVE-sTeoconane-95 ---Page Break--- ™ TABLE 26, IODINE MGR UEISITY (1), ENON MGR DEUSIFY (x), CONTROL FLUX AND NEGATIVE REACTIVITY DUE TO XENON BUILD-UP VS. TIME FOR MIRDOZDNG THOR VALUE OF XENON BUILDUP AT 4 GIVI TDar UHR THE FOLLOWING CONDITIONS: OPERATING THERMAL FLUX = 10M, t = 6 HOURS AFTER TERMINATION OF FULL POWER OPERATION, At = 1 HOUR, nar « Do t I x o $1) +. 9BSE9S4EHS

+.797133 906015 +, sitio Sea RES 3 aaa 2Bi0 4.799961 16E016 ougovvv€=99 vOJOUuUE: sizhalagloes6 =} e000000E+1 5 sagagge2 SI2IYEST§ _ssuovsouLvEL SS ene E18 +. 1 S8S0081E+18 —s:700U 0000! 8 EBPOFOUSIENS SeLasura7Est 3 nououuOE= 33 pe Fr ONTARSSTE TS —+.2608 SHSONESTS sso aUDUDE=3S ~ <4°088 ~ SOREL ~eh581 1 STTERTS —=< 33229) a ES siumabse agent HOUR HE 3 adgayooye-39 7122302 he Set: #372 16227E--15 >, sod. UVE=99” 342 "BT #12200 +1 362613676415 1383427616013 WER Epo #32665 at 2 pepzobog7erts =n wonene=8> 14 00 2230261 5 NPTEM§ 42999 =: #5200 32350 SSB EE eens a ia eZ gi 7ROBIENS = 13OReAOE | 417.002 3. 363) iorbSe ‘ 2B7SIB UTE «3570571 DE E 2 vuodGE—39 F137R GH eoaoe=eg 18271 te oo 5969098 -1§ ---Page Break--- Figure 2 Negative reactivity due to after shutdown xenon buildup for various operating fluxes 6 ---Page Break--- necatve reactivity % 0p a g a “TIME AFTER shutdown = HOURS ---Page Break--- soqpreg worvenny, 07009 shutdown ORE Ov 8 NF dnpryna wowex 04 onp Layaryoves eaygaou pamuven pre pesndanormmn 30 wowrswteny “STE Sy ture am ---Page Break--- & woyaesedo snonuyqu0o —- ayy Buyyesedo meses dprmng wousx 04 enp kararaones oaysefon “ETE gy ee ee ee oo Fa STEN TROT OE KAN ---Page Break--- 3 Figure 4. Negative reactivity due to xenon buildup versus operating time — one shift operation ---Page Break--- ---Page Break--- a a CONTROL PERIOD (HOURS) Figure 6, ratio of the optimized after shutdown xenon peak to the peak continues with low level shutdown for several different operating fluxes, for - 1 hour ---Page Break--- ez . a ee CONTROL PERIOD (HOURS) Figure 7. ratio of the optimized after shutdown xenon peak to the peak obtained with immediate shutdown for several different operating fluxes for = 0.5 hour ---Page Break--- Figure 8 Ratio of the optimized after shutdown xenon peak to the peak obtained with immediate shutdown versus steady state operating fuel, for several different control periods (b) 3

---Page Break--- ---Page Break--- 85 Figure optimized after shutdown xenon buildup compared to the xenon buildup

following shutdown in a single step control parameters: Qo = 10^3, be 2 hours, At = 0.5 hours, Onax = ---Page Break--- 4 ~ xenon buildup after immediate shutdown Z. Optimized xenon buildup * | 3 : 3 $$ Snot “Power Hours” ---Page Break--- inure 10 HUMBioptinized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step Control parameters: Qo = 10^av, bs 4 hours, At = 1 hour, Onax = ---Page Break--- > e ~ = / je ---Page Break--- xenon buildup as compared to xenon buildup following single Control parameters: be 4 hours, At = ---Page Break--- ---Page Break--- xenon buildup in a single step ---Page Break--- ---Page Break--- ---Page Break--- ---Page Break--- Figure 14 optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step Control parameters: o = 10M, ba 7 hours, Mt = 1 hour, Oma = ---Page Break--- ---Page Break--- Figure 15 MINEX-optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step Control parameters: o = 10^-nv, ba 6 hours, At = 1 hour, Dna = ---Page Break--- jee ---Page Break--- Figure 26 MINEX-optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step Control parameters: Qo = 10^Fnv, De 2 hours, At = 0.5 hour, daax = Qo ---Page Break--- ---Page Break--- Figure 27. YOMEL-optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step control parameters: do = 10%m, beh hours, Dt = 0.5 hour, Onax = ---Page Break--- ---Page Break--- Binoptimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step control parameters: Qo = 10%a, beh hours, Mt = 1 hour, One = Do 103 ---Page Break--- 10 veoh. ---Page Break--- Figure 19 MMWEX-optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step control parameters: Qo = 10%nv, b = 8 hours, Bt = 2 hours, eae > 1205 ---Page Break--- N, N XN. Fue = Nouns: veoh vol po z eo

ST See . *e e ---Page Break--- Figure 20 HIMEL-optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step Contre parameters: Wo = 2 × 10^5 nv, da Thours, At = 1 hour, Daa = 0 ---Page Break--- ---Page Break--- cure 2 optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step control parameters: Qo = 10^a, vachours, Bt = 22 hours, sax = 0 ---Page Break--- ——s pt $3 3 © © @€ & 8 & @ 8 a 8 Mog AMUIAWIVRN anLLvOaN su = xe ---Page Break--- Figure 22 optimized after shutdown xenon buildup as compared to the xenon buildup following shutdown, in a single step centered parameters: (bo = 204, be = 6 hours, At = 1 hour, max = 20 ---Page Break--- sol. aol ---Page Break--- Figure 23 MOI-optimized xenon buildup for minimizing the xenon concentration six hours after completing full power operation ---Page Break--- egy ALIAUDWRN aniavoaN tT ---Page Break--- as 1. Zoltan B. Rosstéoay and Lymn B. Weaver: Optimum Reactor Shutdown Program for Minimal Xenon Buildup, March 1964, HSE 20 pp 318-323 2. S. Pontryagin et al: The Mathematical Theory of Optimal Processes, Interscience Publishers, New York 1962 3. Kohed Sato: Optimal Power Decrease for Minimizing Xenon Poisoning, Bulletin of the Electrochemical Laboratory, 29 Vol. 6 1965 pp A29-h12. 4. J.B. Prosdalt and A. L. Babb: Xenon-135 Transients Resulting from Time-Varying Shutdown of Thermal Reactors, TARS-4, 2 1961 pp 316-317 5. Y. Shinohara - J. Valat: Optimisation de l'expoisonnement xénon par minimisation du pic xénon 6. X. Shinohara - J. Valat: Optimisation de l'expoisonnement xénon par optimisation de l'incubation ou de la guérison, Comptes Rendus Acad. Sci., Paris t. 259 (2h sept. 1964) Group 6 7. BiB, Mente, J. J. Roberts, H.P. Smith: Limitations to the Applicability of the Restricted Space, The Optimal Xenon Shutdown Problems, TAMS-8, Nov. 1965 pp 480-421 ---Page Break--- [REFERENCES (page 2): % be Led, Roberts and H. P. Smith, Jr.: Time Optimal Solution to the Reactivity-Keeping Shutdown

Problen, NSE 22, 470 1965 M. Ash, B. Belieann, 2, Kalaba: On Control of Reactor Shutdown Involving Minimal Xenon Poisoning, NSE 6, pp 152-156 1959 A. B. G. Sloadi and A. Sanchez: Xenon Buildup Under Various Operating Conditions in the Puerto Rico Nuclear Center Research Reactor, PRNC - 63, 1966 Apr. R. V. Meghreblian and D. K. Holmes: Reactor Analysis, McGraw Hill, Inc., New York 1960 M. Ash: Application of Dynamic Programming to Optimal Shutdown Control, NSE 24 No.2 Jan, 1966 pp 77-86 R. Bolimann: Dynamic Programming, Princeton Univ. Press, Princeton, N. J. 1957 (Chapter 1) B. Bolimann: Adaptive Control Processes - A Guided Tour, Princeton University Press, Princeton, N. J. 1961 (Chapter 6) M. Ash: Nuclear Reactor Kinetics, McGraw Hill, Inc. New York 1965 (Chapter 6) ---Page Break--- REFERENCES (page 3): 16, M. Ash: The Xenon Minimax Problem IA-968, Israel ABC, Soreq Research Establishment, Yarneh, Israel Dec. 1964 17. J. Buret et A. Ly Garofa: Influence de l'Empoisonnement Xenon sur Le Controle et la Sécurité des Piles à Haut Flux, Reactor Sci. & Tech, (Journal of Nuclear Energy, parts 4/8) 16, pp 209-219, Pergamon Press M. Ash: Optimal Shutdown Control of Nuclear Reactors, Academic Press, New York 1966 ---Page Break--- APPENDIX 2 Flow chart and program Listing for PREX —— a FORTRAN program, written for the IBM 1620 computer, to determine the xenon-135 and iodine-135 number densities as a function of time, for arbitrary operating fluxes ---Page Break--- START NUMBER OF HOURS to compute TAN Xe CONCENTRATION, etc. | OPERATION Flow chart of PREX program compute TIME SATURATION | concentration. COMPUTE IODINE AND XENON SATURATION values COMPUTE IODINE DECAY and 0F XENON LOOP SET FLUX to 2680 "more hours" for compute Print AND output ---Page Break--- PREX flow chart (continued) SET FLUX to ZERO compute IODINE AND XENON CONCENTRATION. COMPUTE IODINE AND XENON DECAY SET Flux TO GIVEN VALUE input parameters ---l_ GUNGEXe @ 1 VALUES TO SATURATION [Sanraacr

ve TS VALUE, Yo THE FLUX EACH HOUR. compute CONCENT. La © ---Page Break--- COMPLETE DELAY OF XENON er Flux To GIVEN VALUE Mw INPUT ---Page Break--- ae { Fae flow chart (continued) se ---Page Break--- Listing of the PREX-program revo concentration e#aciAn Biss € tot Eo Cs eusyom ren (10) 610,68 10), TACO) SF (10) FLLA(10) BETA? tose Poke. , oan Fein cee. a.en 5 e14.8,608.8) 8, £148 €18.6,098 2542) eiksecettsb exe. 'Sittin f14.6 ion ie uxas v4 8 See TA te 16x, tt TK 1,161,200) a ie ane Sehr, BEE iy 2148) ? he, 19, if Teteelse'swaren 312.3 oe Bose 5 Bie : Barge brad Naot car sich Bias BAS EAL As un norte ete eam towne so ay 'eo. BBE a atres Bsey "AAD ibopsuastazeract yy Beate READ DGS LAST HEnnCL Ty (1 1).0HC0 1) PACLITD,CSFCOTD Byes trastoa, Barto 5 Irs0, Beeb retreat yen ° Heao" doa tas reoxttr) Tease Resacurae ao toys Seale onsen rat doe ete erin 33.) TI KT) Yas. Seed RT) areola hs: Sods) Spo Tee Ut pe, SUSE UTD Siorestsnct A230 seFEstareéain FeTSpibe surrey a) 11.12 one, Foon etna) Telsense a 3)50, 51 'peta 2008 buen Foo Fineeo.0 Geor8 GoFat 4,13) rast es apts ---Page Break--- 1980 RRSEE TE: 2k, Listine of the Fii-program (continued) TmEaTINe oer 2a mene ZEYACAT)/¢EACCHT) UY AZETACAT} 5-790 tetera suite 9115506 16 mun 2008 HERES EL LENO sq fo ecg tay reese Bana a 5 iAH Oncr ART SUPER 1990119.19. 1% 4 7103, 25426,27,95.46) sACOME a7 thet Stbas ao meee 8), 708M) oH HTrH}S3, 33,44 ag fend) Bale Eot0! fy Soxtar Soe GOTO nt 2 T13p7Ue, 7179.4 BR fo You ban, Poa, pat Sena yup Go f0CNm, 715) mK Th at ---Page Break--- 325 Listing of the #X-program (cont smved) 3 7a2 «40> ie "it Be i Been tnt eo eer ccch emu aeeenreaerca a Ree 73,745, Re plsetasste Yoose 7? ee Teast 76 Ot mS Oe re 997 Soy 7 ati 5. SRE og Fecteome@s 3008 0 san we Beas AS Ue ecaahanasTs° ---Page Break--- aprox 2 Flow chart and program Listing for MINEK -- a FORTRAN program written for the 1841620 computer to minimize the after shutdown xenon peak as a function of the control 'fu pattern ---Page Break--- Flow chart of MIlicX-program azn \=/ ame —— ar *. wee me ; =e

Co pi T wa ws ---Page Break--- Flow chart of MINEX-program (continued) @ yore. L_,_] INITIALIZE economic vector index. eso Gray XusxGl, Yoeve! eae x very TABLE mo Decision index. sro. noe Kaet f. Q asia Ea nl ben veer +e) . fr onc 6S x INDEX oon See : oO" : 6s =a a Sones Pa se att er nots i wwemses GS) = Pecan a ven rs ere = ---Page Break--- 2 ---Page Break--- Flow chart of MINEX-program (continued) ---Page Break--- Flow chart of MINEX-program (continued) penser on ese FOF ale SLE BPEALTES XS ---Page Break--- Lai ooildiod:a | FO 1 O O10 O 1 O14 ---Page Break--- Flow chart of MINEX-program (continued) reo mm enw " nent eee | sina yrrerts 6r1/3600 — lxasaw + xastsd asi = vast no.“ 00 sarisries ---Page Break--- Flow chart, of MINEX-program (continued) FR = FT oor + va Pua» Fa) E vooe + YG! 4 wx = Fo) XENS = x62 ‘yoos = vez Ss pura = roy Sa. Fuuxs + Pen) XENS = x64 vyoos = Yee cs FLUXG = FIRS! Fuuxo + FKD) ENG + x05 ENO + x69 Yoos = 65 ooo + veo : ux? = Fin run + Fo xENT = x66 ENN = x60 yoo? = vos yooH = Yoo ruuxe = Face xene + xo7 oe + ver So a PLUKD + FO) uve = ace XEND = x68 ENS = xe yous = vos YOOS + Yo ---Page Break--- Fide chart of MINEX-program (continued) FLUIS = Foc xen + Kew Yoo + 618 rc Leon = us ---Page Break--- ---Page Break--- yr Flow chart of rpurt-program (continued) —t_ vx > Xeni VE + Yoo! ve = Fux! 3. ve xen ve xen vt = yoo lve = vooe ve» Luxe Ve = FLUXS forrxee kours 4 kours 6 eee @) \vr + Fuuxs [vxexens rors # vt = voos vr = LUXS oO. ---Page Break--- ---Page Break--- Flow chart of MIXEX-program (continued) 0 = END et fo Wx n0x-2 taco vam0n| 339 ---Page Break--- uo Flow chart of MINEX-program (continued) ---Page Break--- Listing of the MINEX-program, WL WE X CODE APSR DIMENSION FCS), XAS (50), YAS (St), KASH! 6), YASGL 52}, O6T(15} 131 132 3 125, 0%, YX,AcK $25,015 TL, ACt 12s.F oc, Acs 7 HPL, XZ, VE TaohaF} 2, ch, 7xv, ror bey Ve i25.a0r(s) Tes, LWDaw EcOtiet ate GO 10 4g 6 XGdext. yeraye Qu 7 X2e2-1 pt=p6T(2) GO TO ne © X62=KL Yo2ny' EFIND=2 3133, 133, Go TO 4G 11 XG3=xt YG3ay!. EP (WD=3 1 34,

1316,12 13 Keay Tevet (4) XLexG3 ---Page Break--- s+ + «4 —a ss 4 1 1 1 4 4 " 1 4 4 Al 1 qT q q q th q qr qv q Listing of the KIN@~program (continued) YLevG3, FLaF (Kis) KOUTA Go 10 48 Ve XGuexL Your FF (ND~)135,135,15 15 KSat 16 Koukset OFADET(S) XLexels Fn (KS) 17 XG Sex Yo5e¥L F(o=5)136, 136,18 20 XG6=XL ¥t 21 7: 22 x7a¥74 ate) XLoKCS vusto’ Far (47) KO0T=7 G0. To. us 23 A67=Kt vere rt, VE CID=799 36,138,246 24 m0 25 Kimiiny oregatte) XUatu7 Yeever Flak (a) any Go To ut sega. vahert 1ECO~E $439,139.27 27 Kat 25 Kewseet oTabGTE) xhexGe wusrar 26 ---Page Break--- se ISIS IS BENE, Peres 2 SERS SSS ST Serse8s Listing of the MDNEI-program (continued) 29 et 1CWO-5) 140, 140,30 LS WEE DT=DGT(10) FLaF(K10) KOUT=10 Bee HF(ND=10)141,141, 33 33 Ki1=0 OT=OGT(11) eal FLeF(KI1) pAno~11) 142, 142,36 vEE DT=0GT(12) ae YLsYGIt FLaF(K12) a GO TO 4B 38 XGI2—xL JF (NOm12)143, 143, 39 HO K13eK1 301 oT=oGT(13) XLOXGI2 YeeyG12 Eber (13) KoUT. 41 xG13exL TeUiost)104, 14442 42 Kibo M3 Kiba KI yet Dt=oGt(14) XLaXG13 YumYG1 3. Fiori) KOUT =| 4, GO 7048 fh XG ex YG1haYL ---Page Break--- Listing of the MINEX-program (continued) VE (ND=14)145, 145,45 45 K15=0, NB RISK get or=pcT(5) XLaxXGts Yuayors, FLaF (#15) KOUT=1 5 GO 10 jig 7 XG1 SeXt. YG15a¥L Catlett G0 TO 124 48 Ta0. ho TaT+€l DED =CI (YI #F CSCHFL-DI*YL-ACI AYL°FL) YLeVL+0E | (mC (YX"FESEMFL EDI MYL=XL*(DX-ACX*EL)) 1E(XL)125, $0, 50 50 1F (T=0T)49, $4 51 51 GO TO(52, 56,123), Loon 52 GO 10(6,4,14, 18, 47,20,23,26,29, 32,35, 38 1 ,44,47), KOUT 53 T1T.o. 00. SH" Jat, NO TrtetTsD6T(J)/3600. Shh CONTL WE 55 TPlmIPI+. NTP =TPI YAS(NTP] JY XAS (TPE =XL Feo. LcONe2 60 TO 48 * 56 VEC TTTATKV) 57, Sy tet t-0et i 875600. G0. 70.55 58 PEAKaxt GO T0(52,60),1 60 IF (PEAK-PH) 61, 61,76 41 PitmPEAK 00-62 Jat ,uTPE op, XASG(.))@XAS (1) ‘62 YASG(:))=YAS(0 FLUXI=F(AT) XEMAXZ ¥ Ti 2=TP] 63 HGISERD§ 57 3 XENB=xG2 yoo3=¥G2 ---Page Break--- as. ‘ating of the MINEY-program (cont.Amued) 1F(W0~3)75.76, 64 6s FUUIXbat (Ki XEN =XG3 YODA, TE (ND=HI75, 75, 65 65

FLUXS0F (3 XENSeXGL YOvSaYGh 1E(0-5)75, 75, 66

66 FLUKG=F(73) KEN eXGS YOD5=YG HED) 67 FUIKj=F XEN7axKG you're 4ECNO=7)7: 66 ELM x oF (XE NiaXG Yom es IF (iD 7 5,76, 50 6 FLUXD=E (S03 XEW=xGE YOosmrGi 1€CW=975,75,70 70 ELUX=F (40) KEHO=XG! YODO=Yi 1F(N0=10)75, 76,71 Th FLUTE CATS xEi012xG10 YODIT=YGI0, LFCWU=11975,76, 72 72 FLUIZ=F (c4z5 0" xen aman yoizevary 1F(W0=12175,75,73 73 FA 3aF (43) XEN Gms 02 Yoo 3=¥612 1F(WO-13) 75,75, 75 Th Fltitet (485 XEN beXt1 3 YODT m4 3 5 UFCW 175 95 FLAN Sa C$ XENI 5a YOO Seycinis 75 Ucolet 75,67) Be spo BLS aw 76.75 87 ,85,85,8%,83,82,81,0,7%, 78,77), LAN 0 f (140,80,60 ¢)37,81,81 (aida)3h 2.42 {i 10-31, 6383, KomuF)26 64,84 KEW IZ U565 ---Page Break--- SaResSe Listing of the MINEX-progran (continued) £5 VEC muh y22.85,86 8 TE CRG=HE 1267.07 bp et csmur $88, 8 GB VE CRbaWE) 13,65 580 Be 1FCS=HE}10,90;90 So IECRE=UEIZ AA OT UPC SD=HE) 5,22, 52 2 VkexEul vi=vo01 VR=FAL auUTet 60 0 120 83 VxexEU2 vimvoD2 VE oF SOU faa, Go 10720 pa VE CWD=2I124 121,05 15 VxeXEn3 vy=¥003 VeaPLUKS OiT=3, GO T0120 66 VE(ND=3)121,121,97 97 UXexEnih vi=voou VP=FLUXS OUT a4 G0 70 120 08 TE(MOM 21, 121,08 OP VKRXENS, VievOD 3 Ve=PLURS KouT=5 G0_T0 120 100 1F(ub=5)121,121, 101 VOT VxeXENS visvoos VEmFLUXS KONT=6 GO To 120 Yoo TF (NO=5)121,121, 103 103 VXeXENZ vi=Yob7 VraPLuK? KOUT=7 GO 10 120 10h TF(ND=7)421,121,105 105 VXaxENt Vi¥OD6 VE=PLINAE ‘OUT at 60 70 120 105 1F(uD-#)121,121, 107 107 Vxexen vi=voo. VFeFLUK: ---Page Break--- a a a zn 21: a tn a a a a a z z z ar Listing of the MINE-progren (continued) xouTa9 GO 70 120 108 1F(NO~9)121,121, 100 105 Vx=XENO VF=FLUXO Vi=YODO KOUT=I0, GO 70 120 140 1F(WO-10)121, 121,017 TID VX=XENTT visyoort VESELUN xOUT=11 Go 10 120 VF(HD=11 121,121,193 ViteXENI2 vievoot2 VeaFLUI2 KoUT=12 60 70 120 TE(WD—12)124, 121,115 VXeXENT vieyoo13 VFsFLUT3 KOUT= 13) 60 70 120 116 TF (HO=13)120,121, 117 AV] VXeXENT vievoots Ve eFLUT Surat 60 101 118 TFC WO=1 15121, 121,119 Me) VXeXENT 5 vi=¥oo1 3 wer 5 Kou 120 LiDeLios1 ROm((VX"ACK"Z)/(ACSF* (1 SYD BOO PRINT 125,UND, TINE, VL, VX, VF, RO TIME®TINELOGTELND) 73.600. LEC

ROUT=15)1465, 121, 121. 146 GO TO(73,94,96,96,100,102,104,106,108,110,112,114,116,118), KOUT 121 NTPL=TPI2 LND=0 VF=0.20122 oat, NTPL ROM((XASG (<1) *ACK*Z)/(ACSF*(1.+Z)))*100- XL=XASG(J) YL=YASG(J) PRINT 125)LND, TIME, YASG(J), XASG(.1), VF, RO TIME@TI HE+0GT(16) 3600. 122 CONTINUE DT=DGT(16) Leones con 123°ROLE (RL*ACK*Z)/(ACSF(1.4Z))*100. ---Page Break--- n728 2812 72050 Breve Rese 2380 72484 22992 Bioko Listing of the KINEX-program (continued) PRINT 120, LND, TIME, YL, XL, FL, RO TIME=TINESDT/3600. TE CTIME=TOT) 48, 48,1 124 TPlao. GO TO 53 125 PRINT 728 60 TOY 126 FORMAT(EDS.£, 1.6, £15.8, E146, 614.8) 127 FORMAT(VS, 6) £14.68, £1! 6, 614.6 (618.8) 126 FORMAT(2oftweGATI VE"xEuon" VALUES 425 FORMATCIX, 13, 5%, F6.2,2%,£1.8,2%, £148, 2X, E14.6, 1X, F682) 130 FORMAT(EHDECI SION, 2x, 1TIME, 1OX, TH, 14%, TX, 1 5X, 4HPLUK,OX, 2HRO, /) 131 FORMAT HSH) 132 FORMAT ¥///) 133 LAM 80 19 12% 13h Laitea Go To 124 135 LANe3 60 TO 124 136 LAtsis Go 70 12m 137 LAMe3, GO TO 128 138 Lavies, GO 70 12% 135 Laney O70 12 140 Latte 10 126 Vat bas Gero 128 tia tA%a10 50 TO" 12H 193 Lied Go To 128 tale Latte 50 70 124 15 Lari Go 1 124 ent ---Page Break--- spre 3 ‘The Pontryagin Maximum Principle and its application to the problem of minimizing the after shutdown xenon peak us ---Page Break--- 250 A statement of the Pontryagin maximum principle and its application to minimizing the after shutdown xenon peak is presented herewith. In order to state the maximum principle in its simplest form, the system is described by a set of state variables: x1, x3, s4+y X, and a set of control variables: uy, uy sory ayy which satisfy a set of ordinary differential equations and initial conditions given in the following form dy = YG mys sees mys Uy ty zr Oy =

fabs Xp e wit) (0) = xX) oo at Wy zy very Mgt), (0) = 299 yr Xap veep %) and by the control vector: Te (yy ty voy oy) “ and the optimization problem may be stated as follows. It is required to find a control policy, i.e., the vector Ts uyy tgy cesy ty) which will transfer the above.

described system from its initial state (0, x20 say %qo) into a final state, within a duration T in such a fashion that ---Page Break--- as a certain criterion functional z 3 fl f Fy he Hayes Xi Oy py ones Ut) at, ie minimized, with respect to the choice of Let us now define an additional state variable in the form of: ¢ At S fg Os Typ very HGF Uy Uy cone Uyeda which satisfies the differential equation + tt) say Myb Upp Yop 841 = for Op ty = ‘the initial condition: x ,y(0) 20 and the final condition: Mee Ded Further, let us define a set of auxiliary variables of the system Pap gy see9 By With the aid of the following set of ordinary differential equations and final conditions: 4 = 2, Ofe arr . ma OP By Pet BET Paes PMTM=O -%, = fe fon = a BaP? 2x, Pet *Oe Pasi Pa(T)=O 4 = Qh, Ob an . ae Ont By Pete. + Se Poet pa(T)=O ---Page Break--- <1 By, eo, Shs ROO yar Digs, PALE PralT)= Now define a function it as Werte P2 faeces Pati foe, H ip called the Hamiltonian of the system. From the definition of it, it is evident that the state variables x) %2) +++) %,,1 and the auxiliary +9 Py gy satisfy the following equations: gi = 28 and a opt at = Bu for 123, 2 say nt Ba variables py» Pz» ‘These equations are called the Hamilton canonical equations of the states. From the canonical equations, it follows that p, ,, is constant in time since H does not depend explicitly upon x, 4+ With regard to the control functions uy, uz, +++, ti, the maximum principle requires that they should be bounded, i.e., ai Sui sbi for i= 1, 2, , otherwise the optimization problem is meaningless. With the above definitions and relationships in mind the maximum principle can then be stated as follows: The required optimal control vector Tt, that will transfer the system from a given initial state (Moy Xop +09 %yo) to a final state, minimizing the criterion functional J [u], while state variables are satisfying the differential equations of the system' ---Page Break--- 153. the same control vector that will maximize the Hamiltonian of the system.

constructed as explained above. Thus H satisfies the following equation: nec {F, x0), HH} - u{p(ed, x, w(H)} H is constant in time as can be seen from differentiating it with respect to time: e-S fae + a 2p; and applying the canonical equations, leading to: +E fib & 8} He const. ---Page Break--- In order to apply the Pontryagin maximum principle to the problem of minimizing the after shutdown xenon peak, the number densities of xenon ‘and iodine (X and I) are considered as state variables, x and x3; the flux during the control period b as control variable; the magnitude of the after shutdown xenon peak being the criterion functional x5. Max 18 is computed from the terminal values of xenon and iodine number densities as given in equation (14), page 5 of this paper, so that using x for the iodine number density and x for the xenon number density one gets for the criterion functional: NK b 2X3 does not contain and t explicitly; it depends upon ¢ and t only through x and x5, therefore -» r Ax) Ax X; dM - it 1 Be xg (1 Perde Sal 3 * Oks 4 5 = & Ox | Ox, x: Ox, Bn HEP ~ Ne XI4 FE (YEH + UX eXe~ OE Xe0) is a linear function of ¢, therefore the Hamiltonian H is ph + Paka + Ply 4s also a linear function of 6, so that it can be written as He Bo + terms not dependent on #, where Bids do not depend on #. ---Page Break--- Since @ is bounded, 1. 0, 05 © £ Ono the only two choices that will maximize H will be: oH 20 OH ° for 3G <0 020 me OF OH, max BE 0. Consequently, the control flux pattern that will minimize x, (which is the same that will maximize H [0]), is a switching function between the two admissible extreme values of the flux 0 and Onae. For obvious reasons, this type of control is referred to as pulse type or "bang-bang" control. ---Page Break---