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PUERTO RICO NUCLEAR CENTER

?The Problem of Xenon Buildup in Operating Reactors"

Angel Sanchez del Ro

and

Aviva E. Gileadi

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Angel Sanchez del Rio*

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Aviva E. Gileadi

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* submitted to the University of Puerto Rico at Mayagues in

partial fulfillment of the Feqiirenents for the degree

Of Master in Science (Ituclear Engineering)

Work performed at the Puerto Rico Miclear Center, Mayaguez

(NO, AT (40-1/-1839 FOR U, 5. ATOMIC ENERGY COMMERHION

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UNIVERSITY OF PUERTO RICO

College of Agriculture and Mechanic Arts

Mayaguez, Puerto Rico

?THE PROBLEM OF XENON BUILDUP IN OPERATING REACTORS

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ANGRL SANCHEZ DEL RIO

A thesis submitted in

partial fulfitinent of the

requirements for the degree of

MASTER OP SCIENCE

HOVENEER 1966

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Apstaact

A computer Piai~progran was written on the IEM-1620 to determine 1-135 and %e-135 concentrations and negative reactivities associated with the buildup of Xel35 under various operating conditions of a nuclesr reactor, The one ?velocity point resctor 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 nogative reactiv-

Stes due to Xe-135 buildup tn 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 PRNO resnarch reactor agree with manred values within 16 of A,

The problen of minintzing the after shutdown xenon pea: with respect to the pattern of shutdown 1s treated using a method described by Ash, In this rethod a finite muber of flux changes are allowed pricr to cosplete shut~ dow, ?The sequence of flux steps within a certain ?control period" 1 de~ termined in auch a way that the resulting after shutde:m xenon peak should be minimum. A computer progra -? HOKE ? has bewn written on the TEK-1620 computer to perform this optinization.

Minintaing the after shutdown xenon peak, with the ald of the KINEE code hhas been carried out for a number of operating fluxes, control times and

stepsizes. The results are presented in tabular and graphical form,

MINEL-computied flux values seen to be corroborated by results obtained by

---Page Break---

?other investigators using the Pontryagin Macimm Principle,

?An important advantage of the MINK method 1s its versatility, which per- ite extension of its use to a rather broad class of optimisation problens with only minor modifications,

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Accom,

wish to express sy gratitude to the many persons who ecilsborated An

this work, but ospucially to Dr, fviva B, Gileaii for suggesting the

problea, for vupervising the work, for her advice, help and continuous

encouragemint.

Telco

15 thank Hr. Victer Davila, Director of tine Coupsiar Gexter,

CAMA, Sor hie Instruction on procescing methods end for his Liberality

in latting m2 wee the cecputer dunirz nights and wockends.

Yrs. Anne Esy's moet volvable advice on preparing the ¥DiKt-prorram made
At possible to 2% tho whole program inte the available semory of the
TBHi-1620 ccurpater.

The cosistance of the Reactor Divieion of tle Fuerte Rteo Kuclesr Conver

in the crperinectal vorifieatien of the PEBGprograr ts * ighly erprieistod,

?The generors epersoreistp of the Puerto Rico Water Resources Authority ?
which mage 45 poradble for the writer of this thesis to complete his
studies toxes? the Master's degree ? te herewith gratefully askmoviedzec.

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Mmerical Reoulte Obtained with the Ald of the

Optimisation

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APPENDIX 1.

flow chart and program Listing for PREX ~? a FORTRAN

pregran, written for the IBM-1620 computer, to determine

?the xenon-135 and iodine-135 musberdensities as a function

of tine, for arbitrary operating fluxes. +--+ ee ++

Flow chart of the PREM-progran ss ee ese renee

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?Table

?LIST OF TABLES

?Tharsal fue (4), dodine musber deneity (1), xenon

number danaity {x} and negative reactivity dve to xenon

Dulldup va, tine under 2 moganatt 8 bours on ?~ 16 hows

oft operation during a 5 day week and after tersinal

Thermal flux (+), fodine mumber density (I), xenon

number density (X) and negative reactivity due to xenon

?buildup va, time under 5 megawatt & hours on ?- 16 hours

off operation during a 5 day week and after terminal

stutdown see ee ee ween eee een e eee

?Thermal flux (¢), dodine mmber density (I), xenon

number density (X) and negative reactivity due to xenon

?buildup vs. time under 1 megawatt 16 hours on ? @ hours

off operation during a 5 day week and after terainal

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?Table

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control flux (¢) and negative reactivity due to xenon

bulldup vs, tine under the following conditions: operating

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control flux and negative reactivity due to xencn

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control flux and negative reactivity due to xenon

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control flux and negative reactivity due to xenon buildup vs. tine ?the following conditions: operating

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control flux and negative reactivity due to xenon

butldup vs. tine under the following conditions: operating thermal flix = 10liny, be 4 hours, ¢¢ » 1 hour and mn

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Iodine number density (I), xenon munber density (x),

control flux and negative reactivity due to xenon

butldup vs. tine under the following conditions: operating

?therzal flix = 10lény, b= 7 hours, St = 1 hour and

er

Iodine munber density (I), xenon mumber density (1),

control flux and negative reactivity due to xenon

buildup va. tine under the following conditions: operating

?thermal flux 2 10Uny, b= 8 hours, st = 1 hour and ?

Iodine number density (I), xenon number denaity (1X),

contrel flux and negative reactivity due to xenon

bi ?tine the following conditions: operating

thermal flix = 10''nv, b= 2 hours, st = 0.5 hour and

Oma 02 eee

Iodine number density (I), xenon mmber density (x),

control flux and negative reactivity dus to xenon

buildup vs. tine under the following conditsons? operating

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Sm Hee eee ee cee et eee eee ee BB

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control flux and negative reactivity due to xenon

dutldup va, tine the following conditions: operating

thermal flix» 1005, b= 4 hours, st = 1 hour and

Omar eC eee eee tener tte e eee

Jodine maber density (1), xenon nusber density (I),

control flux and negative reactivity due to xenon

buildup ve. tine under the following conditions: operating

?thermal flux 2 105m, b = 6 hours, 6t = 1 hour and

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Jodine number density (I), xenon mmber density (x),

control flux and negative reactivity due to xeron

taildup ve. time upder the folloving conditions: operating

?thermal flux = 10'nv, b= 7 hours, St = 1 hour and

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control flux and negative reactivity due to xenon,

buildup vs, tine ?the following conditions: operating

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gonizel flux and negative? reactivity due to xenon tne

buildup va, t: ?the following conditions: operat!

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control flux and negative reactivity due to xenon

buildup va, tine under the following conditions: operating

thermal flix = 10M%ny, t= 6 houre after termination of

full power operation, At wl hours ¢ mags gos ere eee «Th

seem

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Fucuans

Figure Page

Negative reactivity due to after shutdown xenon buildup

for various operating {x00 eee ee B

Compariscn of PAEX-computed and measured negative reactivity

Gue to xenon buildup in the Puerto Rico Nuclear Center

Research Wouctor vv ee ee eee ete te eee eee eT

Negative reuctivity due to xencn buildup versus cpersting

tine ? continuous operation se seve eee eee ee

Negative reactivity due to xenon buildup versus operating

Line wove shift cperation ses tee eee cece eee TD

rom, b= 2 hours, t= 0.5

cece leet e eee E

Contre) parameters: 0

hour, max +

YINEK-optinized after shutdown xenon buildup as compared

to the xenon buildup following shutdown, ina sinele step

Control parameters: o- 10m,» 4 hours, t ~ 1 hour,

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Figure

uv

MINEK-optinized after shutdown xenon buildup as compared

?to tha xenon buildup following shutdown, ina single step

Control parameters: \$0 = 10%nv, b = 4 hours, At = 0.5

hour, pmax =9° + +

MMEL-optinized after shutdown xenon buildup

to the xenon buildup following shutdown, in

?compared

single step

Control parameters: ¢0 = 103nv, b = 2 hours, At = 0.5

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after shutdown xenon buildup ss compared

to the xenon buildup following shutdown, ina single step

control parameters: ¢0 = 10M, b = 4 hours, at = 1 hour, pan eO reset tee settee cree rene

MINEX-optinized after shutdown xenon butldup ae compared

?to the xenon buildup following shutdown, ina single step

Control parameters: 40 2 10m, b= 7 hours, At = 1 hour,

MINEX-optinized after shutdown xenon buildup as compared

?to the xenon buildup following shutdown, ina single step

Control parameters: ¢o = 10m, b= 6 hours,At

que ye crete testes ete seen e ees

1 hour,

MnimX-optintzed after shutdown xenon buildup as compared

to the xenon buildup following shutdown, ina single step

Control paransters: ¢0 = 10'5nv, b= 2 hours, St = 0.5

Roury yma 80 eset tees ee entrees es

MINEX-optiintzed after shutdown xenon buildup as compared

to the xenon buildup following shutdown, ina single step

Control parameters: ¢0 = 10\nv, b= 4 houra, st = 0.5

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Meure

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MINEK-optinized after shutdown xonon buildup as compared

?to the xenon buildup following siutdown, ina single step

Control parameters. go = 10!5nv, b= 4 hours, 4t = 1 hour, gmxe yore ee

MINEX-optimized after ehutdow xenon buildup as compared

to the xenon buildup following shutdown, ina single step

Control parameters: ¢0 = 105m, be 6 hours, ¢t « 1 hour,

GME rete t eee e teenies

MDX-optintzed after shutdown xenon butldup as comared

to the xenon buildup following shutdown, in a single step

controt paranetere: go = 10}5nr, Da 7 Pours, St = 1 hour,

Pmt @ cccctetcccereceeres

MINEX-optinized after shutdown xenon buildup as compared

?to the xenon buildup following shutdown, ina single step

Control paraneters: 40

gmx go ret t tect tet eee cee

nv, & = 8 hours, Ot = 1 hour,

Amized after shutdown xenon buildup as compared

?to the xenon buildup following shutdown, ina single step

Control paraneters: go 2 10l5nr, b = 6 hour

gmc 200 vee eee :

bt a1 hour,

MaNex-optintzed xenon buildup for minimizing the xenon con-

contration six hours after completing full power operation.

Flow chart of PREeprogram se ee ee

Flow chart of MIMDK-program see ee eee

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+ 105

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Bagio Equations of Kenon Suildup

?re operation of thermal resctors 1s unavodably aceompanied by the pro-

uction of various fission frammente, Asong these fission fraqmante

xenon-135 has a special alenificance, because of ite enormous thermal

absorption cross section (about 3 x 10° bare). Due to this hure ther

ral aboorption cross section, xenon-135 unavoidably produced durine oper~

ation, tends to shut down the reactor and, as will be seen later, leads

to a mmber of problens closely related to the operability of the system.

In order to gain sone insight into these problens one has to consider

?the mechanians by which xenon-135 4s produced in the operating core, as well as those by which it is renoved from there.

Some of the xenon-135 ie produced directly in fission but the major part of St, sone 95%, 4s created as a decay product in the following radic~ active chain:

WIS PI, rel, cal 5 wl

?he nechanions of removal are: radioactive decay and formation of x=

?wy neutron absorption (xenon burn out).

Using the one velocity, point reactor model, the dynamic equations des- ertbing the tine behavior of xenon-135 and Lodine-135 concentration are

given as:

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Bae Ve EO + APT - WHXO-a,x a)

B= yry0 - a, - wo @)

ware

X te the mmber density of xenom-135

As the number denaity of Sodine-135

Ty 4s the macroscopic fteston cross wection of the

reactor under consideration

Yq Ae the fractional yield of xenom-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 absorptien cross section of xenon-135

Yor 4s the microscopic cross section of todine-135

to the neutron flux which, in the case of the one velo-

@)

city point reactor model, is given as the function

of tine,

To above aysten of differential equations determines X(t) and I(t) 4.

?the xenon and iodine muber density as a function of tine, provided that

the tine pattern of the flux, Q(t) and a set of initial conditions X(0)

and I(0) are giv

?The analytic expression of the general solution is given by: (See Ref, 12)

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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

to 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 EqMbeing the macroscopic absorption cross sections of

?the poison, fuel and aoderator respectively, The value of negative

reactivity due to the presence of xenon-I35 is an important piece of

information for the reactor operator, since adequate amounts of excess

reactivity to coupensate for xenon poisoning have to be included in the

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reactivity taventory -- 1f the reactor 18 to be operated for ary appre~

ciable length of tine,

1+, Zquilibrium Xenon Poisoning

If a reactor is operated for a long enough tine at a constant power level

(as 4s nomally the case with power reactors), the xenon buildup reaches

equilibrium i,

4 point when the rate of xenon-production from direct

fieeioning and from the decay of iodine exactly matches the rate of dos

truction by cecay ard by neutron capture, This value, the equilibriun

xenon concentration, can be computed at once from equations (1) and (2)

by eotting

qa)

a2)

Mais ?equilibrium xenon poisoning" is a significant figure that has to

bbe Ancluted dito the dnventory of the exsese reactivity required for the

contimious operation of the reactor, e ean be sean from equation (12)

?the oquilibritu xenon poisoning depends upon the value of the constant

operating flux; St snereases as flux inoreases to a Limiting value of

Prag = 5 a3)

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Ir the reactor has to be operated on a continuous time schedule appro

priate compensation in terns of excess reactivity has to be mde in order

te overcome equilibrium poisoning.

Lie, After Shutdown Xenon Buildup

Vile the value of the oguiltteiun xenon potsoning is Linited to 5f AK,

the xenon bulldyp after shutdom may be one or nore ondors of euynituds

roster ? and the problene aesccisted with overriding At may becone very

severe, Af not unsursountabl

Shutting down the reactor i.e, dropping its operating Mux instantly fron

?the constant operating value to

jentially zero, causes a sfjtftoant

Acceleration in xenon production due to the vanishing of the lange flux

dependent negative tern Yo°Xt) in equation 1. Thus the xenon ecneen~

tration begins to build up ewiftiy after shutdown, and it comes to a

peak value where xencn production ie exactly compensated by xenon decay.

Since in the shutdown condition the fodine supply is not replenished,

further decay of edine inte xenon reduces xenon producticn blow xenon

Gestruction and a slow decay of xencn sete tn that S9 completed wlthin

40-50 hours after shutdow. ?The value of the after shutdom xenon peak

4s sensitively dependent upon the operating flux pricr to shutdown, Te

value may be computed fron equations (1) and (2) a

»

Yeax = {To + (1- wddx XoPRIe aay

{To +t Ro} (1-Dare ES x

ware Ijand are the terminal fodine and xenon munber density, vésch

ars eapntet pen the eprating ac Qs can be

12 from equations

(22) and (22); 0 that Kyi, 4s also dependent upcn the operating flux,

---Page Break---

prior to shutdom, A fanity of curves representing afver shutdown xenon

poisoning as a function of tine for various operating fluxes (Fic. 1)

gives an idea about the magnitude of negative reactivities involves

The

fact that there are a number of high flux reactors operating at a flux

Level Os 10" ny and hicher makes the optinization of the after shutdown

xenon peak an actual problem,

1-4. Scope

?The musertca value of the negative reactivity dve to the presence of

xenone1J5 in the core is an important plece of data, It indicates the

anount of excess reactivity that has to be included into the reactivity

Anventory in order to compensate fer xenon bufldup, For equilibria conditions this value can be conputud sisply frua equations (8) and (12); for tine variable flux patterns one hes to integrate equations (4) and (5). A computer propran, MBL, to perform this integration has been written for the JEM-1620 computer, using the FORTRAN computer Janguaze,

In an attenpt to test the validity of these ecputations, e 52 hour long. xenon buildup experinent was performed on the PRNC research reactor, and ?tho measured negative reactivities due te xenon buildu were compared with ?the values computed with the aid of the PHEK program. The agreecent is YerY eutiatuctory, the deviation being within x AK, (Fig. 2)

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After the validity of the PRX prooran was thus tested, PREX was used te compute negative reactivities due to xenon buildup during operation and after shutdom, for a variety of operating schedules and power levels of

practical interest.

?The second part of the work is devoted to the optinization of the after shutdown xenon peak, As stated in Section 1-c the after shutdown xenon

poisoning may reach several hundred dollars.

Restartine such a reactor any tine after shutdown may be very difficult

? Af not impossible. Loading the required ancunte of excess reactivity

In the form of additional fuel may be unsafe or at least very disadvan-

tageous from the point of view of neutron econony, cost, ete.

In ender to overcone the abore described difficulties it has been prom posed by several authors to mininize the after shutdown xenon peak, by allowing a certain tine interval, called "control peried", between the termination of fill poer operation and the tine of complete shutdown, During this control peried the flux should te varied 4p such a way that 4 should result in a minindaed peak after complete shutdown, The prow Mies then cenofsts in optimising the Mux tn the control period with the intsal after shutdown peak ae a perfornance index 4, e. detersining the ?Mux pattern during the prescribed control period in such @ fashion that

it should lead to a raininized xenon peak after complete shutdown.

In on attenpt to solve this problem a FOXTRA!-procran HINEX was written (hppendix 2)

---Page Break---

fon the IEH-1620, using the basic principles described in a paper of Ash, BeLimann and Kaluba (Ref. 9). As will be seen, further, MIX not only furnishes a numerical solution to the mintaising of the after shutdown enon peak, but with very slight modifications can also be used to sclve 4 number of related problems such as mininising the xenon poisoning at given tine after complete shutdown or minimising the contrcl period nec cessary to reach a certain given minimm peak, etc, Besides its fexibil-sty and versatinity this

olution has the advantage of supplying an actual ?optimal shutdown program, using not all too long computing tines on the TBN-1620 ? which 1e the only readily available computing facility for students or for PRIC staff, It is estimated thet the ruming tine of this Program cn an IHNW7090, or a similar size computer, would not exceed a few minutes,

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2. SURE, OF UE RELSVANY LITERATURE

?the probles of optinizing or at leust reducing the after shutdown xenon peak by weans of varying the preshutdown operating flux in a suitable manner has been the object of many investizations. In order to cain @ better understanding of the backeround of our optimization solution, &

brief survey of the relevant Literature is included herewith:

dal and Babb (See Ref. 4) proposed various tine varying shutdown

ethods to Saprove the after shutdown xenon situation ? without obtaining an optimun solution,

Rosetécay ané Weaver (See Ref. 1) optintzed the after shutdown xenon peak ?using the Pontryarin mucimss principle, The Pontryarin maximum principle is outlined in Appendix 3 of this report. Since the llaniltonian of the syste contains the contre) flux as a Linear variable, it follows that optimun control leading to the mininization of the after shutdown xencn peak consiste of a munber of svitehings of the flux between sero and ite naximun value, Qo, 4, ?. the type of control referred to ae a pulsed control or "bang-bang" control, To determine the optinun mmber switch~ings the authore used a trial and error nethod.

Kohes Sato (

buildup after shutdown ae well as after power reduction, assuming that

Je Ref, 3) considered the problem of optimization xenon

?the power level after reduction will remain constant. His treatment is ?aloo based on the Pontryagin maximum principle, lle obtained solutions

for six problens; using the fluxrate and the inves period as control.

variables and the after shutdown xenon peak and a minimin xenon value

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at a given tine 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 ain mization of xenon polsoning at a given tine using the nethede of dynante programing, The results of bis computations -- carried out on a Philco= 2000 computer with an ALTAC-code called DINPROG ? verify the resulte obtained with the Fontryagin maximin principle, nanely, that the optimal ?flux pattern for a minim after shutdown xenon peak consists of pulse of "bang-bang? control, An enpirical formla correlating the magnitule of the control period to the magnitude of the after shutdown xenon peak £9 siven, In this paper (See Ref, 12) Ash points out that dynante program sing and the Fontryagin saximm principle are conplenentary methods of

investigating optinally controlled processes, The DINPROG progran 1s

Aeveribed in detail ina report of Ash (See Ref, 16).

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3. PREX, A OIGITAL NOTiOD TO COMPUTE NEGATIVE REACRIVIRIES DUE 70 XEVON

BUDLDUP_UWER GIVEN OPERATING CONDITIONS

3+a, Mathematical Node) of the PREX Code

Numerical integration of equations (1) and (2), furnishing the Sedine and xenon concentration aa functions of time, were performed with the aid of ?the PREX code, written in the FORTRAN language for tho 1B%-1620 computer. Jn order to make the probles: amenable to digital solution, a suitably

small tine interval At 1s chosen and the differential equations (1) and

(2) are converted Ante éifference equitions 8 follows:

dr =[¥,E¢ - NT -WLOlar as)

Ax 0 [ded «eZ -ax - WE xolar a6)

?The mumberdensities st tine t+ t are determined as:

Xte Ot) = Tt) + Or a)

x(ty At) = x(t) + ax aa)

Using this step by step approximation PREX permits evaluating the values of the Lodine and xenon mumberdensities as well as the negative react Avities associated with xenon-135 as functions of tine, for any given =e) Murpattern and for a ziven set of initial conditions XoaX(0)

? TooI(0), The flow diagran of PRX a¢ well as a Listing of the program

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a

?are given in Appendix 1 of this papor. (See also Ref. 10.)

Bed. Comparison with the Experiment

As mentioned before, the validity and the accuracy of caleulations, per~ formed with the aid of PRX, were tested against experinestal data, ?The ?testing experinent was performed at the Puerto Rico Ihclear Conor Re- search Reactor with the participation of the 1964 Advanced Reactor Lab= oratory Class under the supervision of Dr. A, Gileads, Reactivities in this exporinent were neasured with the ald of a calibrated reulatine rod. The remulating rod wae calibrated with the stable period method

Ancediately befere the performance of the 52 hour long experinent, No

chanres were nade in the core confiruration after the calibration was

completed. At the bezinnine of the experinent the ore was xenon-freo,

After the control rod had been calibrated, the reactor was broutht to

igh power, about 1 Wi, and was put in automate mode, The red positions

were recorded at regular tine intervals and with the aid of the cali.

bration curve the reactivity chanres were evaluated and plotted. After

42 hours of high power operation the reactor was shut doxm and dsmedi-

ately after that brought to a very low power level of sbout 30 watt

This power Level, being several ordere of magnitude snaller than the

?operating power, corresponds to zero power from the point of view of

xenom135 production or burn out. The buildup of the after shutdown

enon peak was observed and followed through several hours after the

?Peak was reached, Simultaneously the xenon-135-caused negative re-

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activities were computed with the aid of the PHEX code using paraneters

appropriate to the materials composition of the Puerto Rico Nuclear

Center Research Reactor, Neasured and Pilx-conputed values are com pared in Table) and represented graphically in Figure 2, As can be seen

from the table, as well as fren the diagran, the agreement is within 1%

ot x.

5

Be may be concluded fron here, then, that the Paii-eomputed values of the negative reactivities due to xenon buildup can be reasonably trusted, and ?that PREX-cosputed values have @ good enoweh accurary to determine xenon caused reactivity requirenente to be included into the reactivity Savent~

ory of @ reactor, This establishes the value of PRE ao a design tool.

Jeo. Xenon Associated Reactivity Requiresente in Various Operating Hodes Computed with the Aid of PREX

PREX was used to determine xenon associated reactivity requirements under variots operating codes, The operating modes considered wore ?chosen with actual operating schedules and power levels in mind, including:

1s Steady-ctate operation, at 11

2, Steady-state operation, at 2 i!

3. steady-state operation, at 5 6!

4k, Gue-shife operation, at 116!

5. Ono-ahift operation, at 2 18

6, Onevshise operation, at 5 14

7 Twonshift operation, at 1 101

---Page Break---

?Two-shitt operation, at 220i

9. To-shift operation, at 5 HW

Jiegative reactivity due to Xg-135 buildup, as a function of operating

tine, under the atove uentioned operating conditions, is presented

graphically in such a way that nerative reactivits

?up in operations of the sane type, but at various power levels, can be

compared, (See Figures 3 through 5), Tables 2 through 10 contain the

computed concentrations of 1-135 and X?-135, as woll as the negative

reactivity due to the buildup of X-135, The xenon concentrations are

siven at each hour, but the couputation is carried out with At = 5 nin,

?due to xenon build

in order to minimize tho error due to replacing differential equations with difference oquations.

From the above diacrans and data one can see thet the negative reactiv-

ty duo to the xenon tuildup will ronain well der 33A/; only if the

power level cose nct exseod two meranatts, For Sive-negawatt operation

a noactivity aliewance of about 5fAX/y has to be made,

---Page Break---

as

4» Tii& SOLUTION OF THE OPTIMAL SHUTDOWN PROULE:!

2. Method of Solution

The problen of nininizing the after shutdown xenon peak is treated in

this report with the ald of the concepts developed by Ash, HelImann and

Kaaba. (See Ref. 9) First, tho problem ie reformilated in a sonewhat,

more explicit manner, as follows

Te 4s asuned that a high flux reactor is operated for a lonz enough

?time, 90 that xenon and iodine are present in equilibriun concentration (given by equations 4 and 5), At a certain tine St is decided to shut down the reactor. liowever, instead of shutting it down by reducing the value of flux from to zero in one otep, a certain tine interval, the control peried b, is allowed between termination of the operation and complete shutdown and in this control poried the flux will. be varied in euch a way as to result in a minimum xenon peak, after complet

shutdown.

?The problea is to determine the flux as function of tine 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 minim with respect to the choice of Q(t) in b, In order to determine the optinal flux pattern in the control period, let us note that,

tthe magnitude (and also tine of cecurrence) of the after ehutdoyn xenon peak is determined by Xp, Ip, the terminal values of xenon and iodine mumberdensities at the nonent of complet shutdown. Further, the values

---Page Break---

of Xp and Ip are deterained ty 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 peek value Tyge 18 @ functional of the flux

pattern in the control period, b, Our purpose is to determine O(t) in

bin auch a way that At should mininize X,,*. This we shall do by using

an approxivation that makes our nethod amenable for digital computation,

?fo achieve this we shall divide the tine interval b inte m subintervals

each At tong, #0 that

nxde ed

and then we shall determine the value of Q(t) in each of these subinter-

vals, considering (Xt) constant in each subinterval. This step dirital-

420s the probles: instead of having to determine Q(t) in b, 4% 49 suf

Hetent to determine Oy, Qpeseen a set of constant fur values An each

At tines interval, Ry makeing At saad? enough thedy, Oye--+ dn se

?quence thus deterained will approxinate the optimal (t) ind, Beside

?the parameters b, At, @, Xp and Ip the value of Lug, is dependent upon

te chotce of the , Opeese On sequence; theratore, to ach shotoe

at the set Oy, Qyeeve ay ona can caleatate the stable ge Velie

ety sang woe of the PEEK computer sate desertbed in Ghapter 3

of thts pape.

+ On

ith thie in nin oar prbien of Hinting the opti ©, ©

sequence is reduced to the following steps:

---Page Break---

On

a, Bhuberate all the possible chose

of eet Oye Oe

under a piven ®, 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, controt pertods ran fron .5 hour te 8 hours,

sizes of the subintorvals varied between .5 hour and I hour, In certain

problens the control flux was raised to twice as high as the steady op-

erating flux, under the assumption that operating the reactor at this

higher pover-level will not be a safety hazard 4¢ continued for a short

?ne-intorval only. Our results indicate that using 2 Qo instead of o (tor naz) doos not inprove optintzation results significantly.

Characteristice of the probleas solved with the ald of the KINEE code,

?together with the resulting control flux sequences, are presented in

?Table 11.

---Page Break---

w

Figure 6 shows the ratio of the optimized after shutdown xenon peak to

?the untreated xencn peak vs the macnitude of the control interval b for

various fluxes. As can be seen, the results inprove as the operating

?flux increases; with an @ hour control interval we cet a peak reduction

0 00% at 3 x 1019 mux but sist xith a 1015 sux, The eubtntervel

At = L hour,

Figure 7 shows the sae values for At = .5 hour.

Figure & showsP (b)/P (0) vs.

control periods

ondy stat

?this family of curves also shows a very definite in

operating flux, for various

Provenent in optimteation with the increase of the operating flux as well

?a9 with the inerease of control tine.

Figures 9 throwh 22 show the diagrans of MINK optinized after shutdown

xenon buildups compared to the xenon buildup for the sane operating ?ue

following a shutdown in a single step. The optinizing control flux pat=

?torn is also Snclud

?re, Application of the LINX Kethod te other Optimization Problems

Tt can be shoun that with very slight modifications the 2I"RX method can

be applied to perform other optimizations besides the mintnization of the after shutdown xenon peak, described in the previous sections. Optim

ination problons that can be solved with the MIIGX method include the

?so-called xenon minimum and the xenon tine optinal problem. ?The xenon

---Page Break---

ainimm probes can be formated as follows:

A reactor 2 operated at rated pover level for a long enowh tine to per=

ait the development of equilibrium xenon concentration, It 4s decided to

shut dom the reactor, allowing a certain given contre) ported b. ?The

xenon minim protien conatste in determining the control flue pattern

4n the control period that will lead to a minimun xenon concentration at

a civen tine T>b, Using the sane argusent as in section ina,

Page 17, the optisal control pattern will te of the "bang-bare? type and

the steps of optintzation will be the following:

a, Bunerate all adaiseibie choices of the control flur set

Pr Opes On, alt together 2 in number,

Using the PREX code compute X(T) pertaining to the first

aéntsaitle set and store,

©. Repeat step (b) with the next admissible chose compare

?the two values of X(7), discard the bigger, store the

?aller of the two and also store the pertatnine i, 2

seve On set.

Gd, Repeat step (c) ?- until all the admissible choices are

sed up and the Last set of Ors Qyreee Gn stored 4s the

required optimising flux pattern for a given b, At and Qo.

4s can be seen, the only modification consists in using X(7) instead of

Yuax #9 8 performance index, A sample problen for minintaing X(2) vith

?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

Fesults in a reduction of xenon-caused negative reactivity to 52 of ite

---Page Break---

?uncptinized value, The detailed results of this run are included in

?Table 12 and represented in prapbical form in Ficure 23.

The tine optinal xenon probles consists tn deterninine the cininal eontrel

tine necessary to reduce the after shutdown xenon peak below @

given value, The solution of this problen requires tho following modification:

a, fin 8 KINGX problem with b= o and ccapare the resutin?

after sluutdown xenon poal Iya With the given value of the problen. If

Sto Yqax 42 sualler than the given value, we have the sclutien;

Af not,

g0 to step by

b. Increase » ty At and repeat step a.

The required mininal b ie the first b which will lead to @ smaller after

ahutdown xenon peak than the value specified in the problea.

?thie problea has not been run on the Ts\-1620 because it would require toc

mich tine; however, {t can be run with no diffiowty on a bigger and quicker

computer e.g. the IS7090 or TBATOPA.

---Page Break---

5. SURBARY AND CONCLUSIONS

Sa, A computer code -- PUK ? has been written for the Tii-1620 in the

FORTRAN Lenquate that Wil] furnish mmerieal values of xenon-135 and iodine 135 matberdensities, and of negative reactivities tied up in xenon-135

for any piven operating, flux and schedule,

Seb. PREX has been used to conpute xenon-235 associated reactivities in ?the Puerto Rico tuclear Center Research Reactor for several. actual oper- ating modes and power lovele, thus determining reactivity requirenents for 1, 2 and § megawatt operations ini, 2 and 3 shifts, Asong other ?things, {t has been determined that the present fuel loading in the

PRNC Research Reactor ie ineufficlont for § meganatt operation.

5c, The validity and accuracy of PREC has been checked against reasured

values in the PAC Research Reactor, and the agreewont has been found to be

within 3% of Ak/g for the case considered.

Sed. A computer code MINEX has been written for the IiM-1620 in the FCR- ?TAU Language to perform the optinteation of the after shutdown xenon peak. this conputer code is very versatile and flexible and with minor modifications St can alec aclve the xenon minimum and the tine optinal xenon

protien, A further advantage of thie method consists in the fact that tts

output oupplies the actual operating data for the control flux program

Leading to the prescribed value of the performance index.

---Page Break---

5-0. Aster running a large munber of MINEX problens, it can be con

cluded that the optintsatton of the after shutdowa xenon peak leads to

Increasingly better results as the operating flux and the control period

Increase (See Figures 6, 7 and 8)-llowever, the increase of the control

flux fronge to 2 Qo does not seen to affect the Iggy values signifi

cantly (See Figure 22).

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?TABLE 1. COMPARISON OF PREX COMPUTED AND MEASURED REACTIVITY VALUES IN

?THE PUERTO RICO MUCLEAR CENTER RESEARCH REACTOR

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?TABLE 1 (Contdmued)

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TABLE 2, THERMAL FLUX (CD), IODINE MUMBER DBNSITY (1), XHVON MOMEER

[DENSITY (X) AND NEGATIVE REACTIVITY DUB TO XEWON BUILDUP VS.

?TIME UNDER 1 MEGAWATT STEADY STATE OPERATION, AND AFTER SHUT-

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TABLE 3. THERMAL FLUX (()), TODING WIMBER OENSITT (I), XENON NUMBER

?DRNSITY (X) AND NEGATIVE REACTIVITY DUE TO XENON BUILDUP VS.

?TIME CORR 2 MECANATT STEADY STATE OPERATION, AND APTER SHUTDON

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TABLE 4. THERMAL FLIX (()), TOOT MUMERR OENSITY (1), TENON NUMBER

DENSITY (X) AND MBGATIVE REACTIVITY DUE TO XENON BUILDUP VS.

?TIME UNDER 5 MEGANATT STEADY STATE OPERATION, AND AFTER

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TABLE 5. THERMAL FLUX (>), LODINE MUMEER DENSITY (1), TENON NUMBER

[DENSITY (1) AND NEGATIVE REACTIVITY DUE TO XEWON BUILDUP V3,

?TIME UNDER 2 MEGAWATT @ HOURS ON ? 16 HOURS OFF OPERATION DURING

A'S DAY WERK AND AFTER TERMINAL SHUTDOWN

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?TABLE 6, THERMAL FLux ((), TOOINE NUMBER UENSIFY (1), KENON NUMBER

DENSITY (X) AND NBGATIVE REACTIVITY DUE 70 XENON BUILIUP VS.

?TDG UNLER 2 MECAMATT HOURS ON ? 16 HOURS OFF OPERATION

?DURING A 5 IAY WEEK AND AFTER TERMIXAL SHUTDOM

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TABLE 7, THERUAL FLUX ()), IODINE NUMBER DENSITY (1), XENON WOMBER

DENSITY (X) AND NBOATIVE REACTIVITY DUE 10 XRNON BUILIUP VS.

?TD UMOER 5 MEGAWATT 6 HOURS OX ?

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DURING A 5 DAY WEEK AND APTER TEROCINAL SHUTDOWN saa:

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TALE 8, THROU, FLUX (¢)), JODDWE HUNGER OENSTTY (1), XENON MNGHER

DENSITY (X) AND NEGATIVE REACTIVITY DUE TO XENON BUILDUP VS.

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TABLE 9, THERMAL FLUX (0p), IODINE WUMBER ORNSITY (1), XENON NUMER

?DBNSITY (x) AND NEGATIVE NEACTIVITY DUE TO XENON BUILDUP VS.

?TIME UNDER 2 MEGAKATT 16 HOURS ON -- & HOURS OFF OPERATION

DURING A 5 DAY WEEK, AND AFTER TERMINAL SHUTDOW ene3es0rns

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XENON BUILOUP, 2 HY, 16 HRS. ON-@ HRS. OFF.

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TABLE 10, THERMAL FLUE (()), IODINE NUMBER DENSITY (1), XENON NUMBER

DENSITY (xX) AND NGOATIVE REACTIVITY DUE TO XEKON BUILDUP VS.

?TIM UNUER 5 MECAWATT 16 HOURS ON ?? e HOURS OFF OPERATION

DURING A 5 DAY WESK AND APTER TERMINAL SHUTDOWN

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ENON BUILOUP, 5 MW, 16 HRS. ON-B HRS. OFF

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XENON BUILOUP, 5 MW,

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XENON BUILDUP, 5 MW, 16 HRS, ON-

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TABLE 12

A SURMARY CP MINEX-RUNS:

CUARACTERISTIC PARAYZTERS AND

RESULTS OF THE PRCELENS SOLVED

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TABLE 12.

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TODINE MUGER DENSITY (1), XENON NUMBER DENSITY (Xx), CONTROL

FLUX (>) AND NEGATIVE REACTIVITY DUE 7 XENON BUTLIUP VS.

?IMG UNUER THE FOLLOWING CONDIFIONS: OPERATING THERMAL FLUE

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+.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

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1

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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

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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

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05203KE+1 6

5462 76E+15

0395106416

5362 SE +15

0039590E+16

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00000008 -99

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?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

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30000000 +16,

2701 3609E+16

11325450315

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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

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50; +

Hronétogdee $

113352226116

124665775+16

133202716415

1393599 66+16

+614683039E+16

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+a 1402837 HE +15.

133087896416

HE

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104962 7E+16,

+10572150E +1

719098798E+16

+962 65919E +15,

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+. 70274052E+15

}.ooc00a008-39

+100000000E -39

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?TABLE 14, IODINE NUMBER DENSITY (I), XENON NUMER DENSITY (Xx), CONTROL

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#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

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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

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FIVBoviOSzE+16 .1 38052 76-15

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7123959910E1§ +193 595220615 +100000000E-95

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?1h4937928e15 +1720091998+15 +. 000000008 -99

SH277IBAGES 3 +:68101314E415 +-00000000E-39 sOUSCOOE-B8

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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

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aux = O°

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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

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412150 1203932996015 | +2257423 56416

313580 °-¥125576250E+16~ + .u2taoeT oE=16

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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

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?TABLE 16, IODINE NUMBER DENSITY (l), KENON NUMBER DENSITY (1x), CONTROL

FU AND NEGATIVE REACTIVITY OWE TO ZENON SUTLOUP VS. 16

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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

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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

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?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

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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

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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,

+ Tooooa0ess 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

Ebooooooe=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

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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

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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 MEGATIVE REACTIVITY DUE TO XENON BUTLD-

?UP VS, TIME UNDER THE FOLLOWING CONDITIONS: OPERATING

?THERMAL PLUK

eax 20°

I

98h M247 66-17

#108701353E917

¥279909792E+17

#271961 3376917

hi 39594617

053517

Susseest?

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 HOUR 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-

+ oeaooooe.

+Toooucooe.

+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

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D

?TABLE 25, IODING MUMBER DENSITY (1), XENON MUMBER DENSITY (x),

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(CONTROL FLUX AND MEGATIVE REACTIVITY DUE TO XENON BUILD-

?UP VS, TIME UMDER THE FOLLOWING CONDITIONS: OPERATING

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eax = 20

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293135GE17 be U0UUvE-99 +101.466,

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+, 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

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TABLE 26, IODINE MGR UEISITY (1), ENON MGR DEUSIFY (x),

COWMOL FLUE AND NEGATIVE REACTIVITY DUE TO XENON BUILD.

UPYS, TO FOR MIRDOZDNG THOR VALUE OF XENON BUILIUP AT

4 GIVI TDar UHR THE FOLLOWING CONDITIONS: OPERATING

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FULL POWR OPERATION, At = 1 HOUR, nar « Do

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Figure 2

Negative reactivity due te after

shutdown xenon buildup for various

operating fluxes

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?TIME AFTER swuTDOWN = HOURS

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Figure 4. Megative reactivity due to xenon buildup versus operating tine ? one shift operation

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CONTROL PERIOD (HOURS)

Figure 6, tatdo of the optinized after shutdewn xenon peak to

the peak cotwines with lawdleve shuiduwn fur several

@Lfferent cperating fluxes, fort - 1 hour

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CONTROL PERIOD (HOURS)

Figure 7. fatio of the optinined after shutdown xenon peak to the

peak obtained with imediate shutdown for several different

operating fluxes fort = 0.5 hour

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Figure 8

Ratie of the optinized after

shutdwon xenon peak to the

peak obtained with tanediate

shutdown versus steady state

operating fue, fer several

different control poricds (b)

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teoptintned after ehutdown

xenon buildup ar compared to the

xenon buildup followine shetéow

in a sin

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contrel paranetors: Qo « 10'3c¥,

be 2 hours, At « 0.5 hours,

Onax se

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4 _~ Yenon buildup after immediate shutdown

Z. Optimieed xenon buildup

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xenon buittup ae ecapared to the

xenon buildup following ehutdewn,

in a cingle step

Control parameters: Qo = 10av,

bs 4 hours, At =i tour, Onax = Oo

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Control paraneti

be 4 hours, At = 04

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Figure 14

vaaioptintaed after shutdown

xenon bufldyp as compared to the

xenon buildyp following shutdown,

tn a single stop

Control paransters: o = 10M,

ba 7 hours, Mt = 1 hour, Oma = Po

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Figure 15

MINEX-optintzed after shutdown

xenon buildup av compared to the

xenon buildup following ehutdow,

ina sinle step

Control paranetere: o = 10-nv,

ba 6 hours, At = 1 hour, Dna = Yo

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Figure 26

MINEX-optinized after shutdown

xenon buildup as cempared to the

xenon buildup following shutdown,

ina single step

Control parameters: Qo = 10'Fnv,

De 2hours, At. 0.5 hour, daax = Qo

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Ecure 27.

YOMEL-optinized after shutdown

xenon buildup as compared to the

xenon buildup feLlewine shutéom,

tn a single stop

controt pareneters: do = 10%m,

beh tours, Dt = 0.5 hour, Onax «bo

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xenon buildup as serpared to the

enon buildup followin shutdom,

ina sine step

controt paranutors: Qo = 10%a,

beh hours, Mt 21 hour, One = Do

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Figure 19

MMWEX-optinized after shutdown

xenon buildup ay conparad to the

xenon buildup following shutdown,

in a sine step

control paraneters: @o = 10%nv,

b eb hours, Bt 2 Pour, eae >

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Figure 20

HIMEL-optinized after shutdown

xenon buildup as compared to the

xenon buildup following shutdown,

in a single step

Contre paraxaters: Wo 2 10'5nv,

da Thours, At «1 now, Daa =o

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enon buildyp as compared to the

xenon buildup following shutdown,

ina single step

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Figure 22

vmmoptintsed after shutdown

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enon butldup folloving shutdown,

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centred paraneters: (bo = 204,

be 6 hours, At = 1 hour, max = 20

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MOI-optintzed xenon buildup for minimising

?the xenon concentration eix houre after

completing full power operation

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Lo Controle et al Séourite des Piles 4 Haut Flux, Reactor Sei. &

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APPENDTE 2

Flow chart and program Listing for

PREX ?? a FORTRAN progras, written for

the 1B4.1620 computer, to determine the

xenon-135 and iodine-135 musber densities

445 a function of tine, for arbitrary

operating fluxes

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Flow chart of PREI-progran

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PREX flow chart (continued)

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Listing of the PREX-progran

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Listing of the #X-prozram (cont smved)

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Flow chart and program Listing

for MINEK -- a FORTRAN prorran

written for the 1841620 computer

to mininize the after shutdom xenon

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Flow chart of MIlicX-program

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Flow chart of MINEE-progran (continued)

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low chart of #INEX-prorrax (cont inued)

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Flew chart of MINET-program (cont inued) penser on

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Flow chart of MINEX-proeran (cont iried)

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Flow chart, of MINEX-progran (cont inued)

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Fide chart of MINEX-propran (cont inued)

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Flow chart of rpurt-progran (continued)

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Flow chart of MIXEX-proeran (continued)

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Flow chart of MINEX-prorrar: (continued)

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Listing of the MINEL-progras,

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Listing of the KIN@~progran (continued)

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Listing of the MDNEI-progre (continued)

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FLaF(K10)
KOUT=10
Bee
HF(ND=10)141,141, 33
33 Ki1=0
OT=OGT(11)
eal
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pAno~11) 142, 142,36
vEE
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GO TO 4B
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38 XGI2?xL

JF (NOm12)143, 143, 39

HO K13eK1 301

oT=oGT(13)

XLOXGI2

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41 xG13exL

TeUiost)104, 14442

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LMsting of the MINEX-progran (continued)

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50 1F (T=0T)49, $4 51

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XEMAXZ

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Ti 2=TP]

63 HGISERD§ 57 3

XENB=xG2

yoo3=¥G2

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as.

?ating of the MINEY-progran (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

youre

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

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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:

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a

a

a

zn

21:

a

tn

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a

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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 T0(73,94,96,96, 100,102, 104,106, 108,110,112, 114,116,118), KOUT

121 NTPL=TPI2

LND=0

VF=o.

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.
```

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n728

2812

72050

Breve

Rese

2380

72484

22992

Bioko

Listing of the KINEX-progran (continued)

```
PRUNT 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 FoRHAT(2oftweGATI VE" xEuon? VALUES

425 FORHATCIX, 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 FORMATO ¥///)

133 LAM

80 19 12%

13h Laitea

Go To 124

135 LANe3

60 TO 124

136 LAtsis

Go 70 12m

137 LAMe3,

G0 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

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spre 3

?The Fontryacin Maximin Principle

and Ste application to the problen

of miniaiaing the after shutdam

xenon peak

us

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250

A statement of the Pontryagin maxinun principle and ite application to

minimizing the after shutdom xenon peuk is presented pereith.

In order to state the saximum principle in its simplest form, the syster

$s described ty a set of state variables: x1, x3) s4+y X, and & sat of contrel variables: uy, uy sory ayy which satiety a set of ordinary dif-

erential equations and initial conditions givin in the fcYlowing form

dy = YG mys sees mys Uy ty

zr

Oy = fabs Xp

e

wit) (0) = xX)

oo at Wy zy veey Mgt) ,(0) = 299

yr Xap veep %)

and by the control vector:

Te (yy ty voy oy)

? and the optinization problea may be stated as follow

It is required to

Find a control policy, 4. e., the vestor Ts uyy tgy cesy ty) wien wild

transfer the above described syste from its initial state (0, x20

sey %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 mininized, with respect to the shoice of

Let us now define an additional etate variable in the form of:

¢

At S fg Os Typ very HGF Uy Uy cone Uyeda

which eatieties the differential equation

+ tt)

sey Myb Upp Yop

841 = for Op ty

=

?the initial. condition:

x ,y(0) 20

and the final condition:

Mee Ded

Further, let ue define a set of suriLiary variables of the systen

Pap gy see9 By With the ald of the folloving set of ordinary differen

?tial 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

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<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 cefinition of it i

Ls evident that the state variables x) %2) +++) %,,1 and the auetliary

+9 Py gy Satdsty the following equations:

gi = 28 and

a opt

at = Bu for 123, 2 sey nt

Ba

variables py» Pz»

?These equations are called the Hamilton canonical equations of the syates.

Prom 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 maxima principle

requires that they should be bounded, i, s., ai Sui sbi for i=

1, 2, , motherwive the cptimination problem is meaningless.

With the above definitions and relationships in mind the maximum principle

ey thon be stated as follova: Mie required optimal control vector Tt,

?that wit) transfer the systen frox 4 given initial state (Moy Xop +09

%yo) to A final. state, minimizing the criterion functional J [u} , while

state variables is

satistying the differential equations of the systen'

---Page Break---

153.

the sane control vector thet willl muxinise the Hantitenian of the aysten,

constructed as explained above, Thus H * setiafies the folowing equation:

nec {F , x0), HH} -

u{p (ed, x, w (H)}

H de constant in time ae can be seen fron differentiating it with respect

to tine:

e-S fae + a

2p;

land applying the canonical equations, leading te:

+E fib & 8}

He const.

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ee

3

a4

Jn order to apply the Fontryagin maximum prineiple to the protien of

miniaizing the after shutdown xenon peak, the nuberdeneities 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 shutdem xenon petk Inge a¢ the criterion functional x5.

%yax 18 computed from the terminal values of xenon and Jodine muaber-

Gensities as given in equation (14), page 5 of this paper, so that using

x for the iodine mmbertensity and x, for the xenon numberdensity 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)

te a Linear fimetion of ¢, therefore the feni2tonian

Ws ph + Paka + Ply

4s also a Linear fimetion of 6, 0 that St can be written ast

He Bo +terms not dependent pon #, ware Bids nat depen

won #

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355

Since @ 4s bounded, 1. 0,

05 © £ Ono

the only two choices that will maximize H will ber

oH

20 OH

° tor 3G <0

020 me OF OH,

max BE 0

Consequently, the control flux pattern that will minimise x, (which te

the same that will maxinice H [0]), is a switching function between the

?two admissible extreme values of the flux 0 and Onae-

For obvious reason this type of control 1s referred to as pulse type

?or "bang-bang" contre).

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