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RESEARCH MEMORANDUM

CALCULATED EFFECT OF URANIUM DISTRIBUTION ON REFLECTOR CONTROL EFFECTIVENESS FOR A WATER-MODERATED POWER REACTOR

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

Two-group theory calculations were made to determine the effect of nonuniform uranium loading as compared to uniform loading on the reflector control effectiveness attainable in a large thermal reactor of present interest in aircraft power application (the supercritical water reactor). The reflectors investigated were a 10-centimeter and an effectively infinite-thickness water reflector, which were considered to be practical for use in the particular reactor design considered.

The reflector-control mechanism considered employs a thermal neutron absorber that can be moved from a position in the reflector far enough from the cylindrical core to have negligible effect on the reactivity to a position at the radial reflector-core interface where it could conceivably absorb all thermal neutrons trying to leave or enter the radial boundary of the core.

The results showed that nonuniform uranium loading to attain uniform radial power production doubled the reflector control effectiveness over that with the uniform uranium loading. However, this doubling of control effectiveness was still insufficient to provide the amount of control necessary for operation of the reactor. Even for the most favorable case considered, the change in reactivity obtained from reflector control was only 0.03 as compared to the 0.132 needed for complete control.

Although the increase in reflector control effectiveness due to nonuniform uranium loading is not large enough to be of use for the reactor considered herein, it may provide the required margin to permit use of reflector control for a smaller, more heavily uranium-loaded reactor, particularly if a more efficient reflector such as beryllium is used instead of water.

Although, for reactors loaded to give uniform radial power, reflector poisoning greatly distorted the power distribution, the resultant distribution was more favorable than that for the uniform uranium loading with or without reflector poisoning.

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INTRODUCTION

Considerable interest exists in the use of the reflector as a means of controlling the reactivity of power reactors for certain installations. By making use of a parasitic neutron absorber in the reflector and varying its position with respect to the reflector-core interface, it is possible to produce a definite change in reactivity in the reactor. This change in position or distance from the interface could be accomplished by several means. For a reflector of solid materials, a set of rods (made of the reflector material) coated with absorber on one side and designed to be rotated on axes parallel to the core axis could be used. For water reflectors, rotating drums or just strips of the absorber could be utilized in a similar manner. In general, the reflector-type control, where usable, requires less space than the more conventional absorber-rod control. However, for water-moderated reactors of the size needed to accommodate the heat-transfer surface area and coolant-water flows required for power application, the change in reactivity attainable with reflector control is very small.

In reference 1, the manner of distributing the uranium over the reactor core volume to attain uniform power production is determined for a spherical water-moderated reactor for three thicknesses of water reflector. The uranium distributions obtained involve high uranium concentrations near the reflector-core interface relative to the concentrations in the central portions of the reactor core. To illustrate, for one of the reactor assemblies investigated in reference 1 (having an 8-cm reflector thickness) the uranium concentration near the reflector-core interface was of the order of three to four times that at the core center; the total uranium investment was about 15 percent higher than that for the uniform uranium distribution case. It is to be expected, then, that the action of the reflector in maintaining reactor criticality is much more important for the case of uniform power production (obtained by nonuniform uranium distribution over the core volume) than for the case of uniform-uranium-distribution; hence, greater control effectiveness should be attainable with the reflector for the case of uniform power production than for the case of uniform uranium distribution. The question arises as to the magnitude of this increase in reflector control effectiveness.

In order to provide an indication of the magnitude of this effect, calculations were made for the supercritical water reactor described in reference 2 to determine the increase in reflector control effectiveness attainable by distributing the fissionable material nonuniformly over the reactor cylindrical-core volume in a manner resulting in uniform radial power production. This reactor design is considered representative of the water-moderated reactors under consideration at present for power applications.

The solution of the poisoned condition in the reflector was accomplished by approximating the control-rod system with a cylindrical sleeve of poison at the radial core-reflector interface. This represents the ideal case or the maximum change in reactivity possible. Since most absorbers are not very effective in capturing fast neutrons, no effect on the fast flux was considered other than the indirect change caused by the difference in the thermal flux. The fast flux therefore was continuous at the reflector-core interface and dropped to zero at the extrapolated outer boundary of the reflector. The thermal neutrons were considered to be entirely taken up by the small layer of absorber; hence, the thermal flux went to zero at the interface.

In order to facilitate discussion of the calculations, the reactor conditions are defined as follows:

<u>Condition (a): cold-clean</u>. - Condition (a) is the startup condition at room temperature, with no fission poison, and with sufficient fissionable material to allow for the contemplated burnup during the life of the reactor.

<u>Condition (b): cold-clean, poisoned reflector</u>. - Condition (b) is identical to condition (a) except that the thermal neutron absorber is in position at the radial reflector-core interface.

<u>Condition (c): hot-burnup</u>. - Condition (c) occurs at the end of the useful reactor life, herein taken as corresponding to 1.3-kilogram burnup of U^{235}. This includes equilibrium poisons. The calculations were made at operating temperatures, to be discussed later, and the condition is taken as critical.

<u>Condition (d): cold-clean condition for 0.65-kilogram burnup</u>. - Condition (d) is a startup condition with everything the same as in condition (a) except for 0.65-kilogram smaller loading of U^{235}.

For each of the reactor cases considered, a calculation was made first for condition (c) in order to establish the proper uranium investments necessary during the life of one fuel loading of the reactor. Calculations for conditions (a), (b), and (d) were then performed to give the changes in reactivity present under the other conditions.

SYMBOLS

F number of fissions per unit volume per second 2932

$H(r)$ power density at radius r from axis of reactor

H_{av} average power density over reactor core volume

H_c height of equivalent bare reactor

H_{max} maximum power density in reactor

k Boltzmann constant

k_{eff} over-all neutron multiplication factor

k_f $\frac{\nu\Sigma_{F,f}}{\Sigma_{a,f}}$ fast neutron multiplication constant

k_{th} $\frac{\nu\Sigma_{F,th}}{\Sigma_{a,th}}$ thermal neutron multiplication constant

L neutron diffusion length

$N(r)$ atomic concentration at radius r from axis of reactor

p_{th} resonance escape probability

r radius from axis of cylindrical reactor

T temperature, $^{\circ}K$

v neutron speed

y fractional yield from fission process

z axial distance from center of reactor

λ_{tr} transport free path for neutrons

λ_{xe} radioactive decay constant for Xe^{135}

ν	average number of neutrons produced per fuel atom fissioned
ρ	density, g/cm^3
Σ_a	macroscopic neutron absorption cross section
$\Sigma_{a,th}^M$	thermal value of Σ_a for moderator and structure
Σ_F	macroscopic neutron fission cross section
Σ_q	macroscopic neutron cross section for slowing down
$\Sigma_{p,th}$	average value of the macroscopic neutron absorption cross section for stable fission-product poisons
$\Sigma_{u,th}$	macroscopic thermal neutron absorption cross section for U^{235}
$\Sigma_{p,th}^T$	total macroscopic thermal neutron absorption cross section for all poisons
$\sigma_{p,th}$	average value of microscopic thermal-neutron absorption
σ_s	microscopic neutron scattering cross section
$\sigma_{sm,th}$	average value of microscopic thermal-neutron absorption cross section for Sm^{149}
σ_{tr}	microscopic neutron transport cross section
$\sigma_{xe,th}$	average value of microscopic thermal-neutron absorption cross section for Xe^{135}
φ	neutron flux

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Subscripts:

f	fast neutron group
o	refers to cases with uniform-uranium distribution at the hot-burnup condition
r	radial position from axis of core
sm	property of Sm^{149}
th	thermal neutron group

u property of U^{235}

xe property of Xe^{135}

REACTIVITY CALCULATIONS

Description of Reactor

The reactor core is a 2.5-foot square cylinder with supercritical water (pressure, 5000 lb/sq in.) functioning as the combined coolant-moderator and with the U^{235} fuel contained in stainless-steel-clad, sandwich-type plates. The core is reflected by supercritical water. At the hot conditions (corresponding to reactor full-power output), the average water temperature in the core is 620° F (kT energy of 0.052 ev) and in the reflector is 480° F (kT energy of 0.045 ev). At these conditions the average water density is 0.71 grams per cubic centimeter in the core and 0.83 grams per cubic centimeter in the reflector. For the cold conditions (prior to reactor startup), the temperature in the core and reflector is taken as 59° F with the corresponding water density of 1 gram per cubic centimeter. Table I presents a tabulation of the core and reflector compositions for the hot and cold conditions. The uranium contents are determined by the criticality calculations for two reflector thicknesses (10 cm and infinite) and for the cases of uniform U^{235} distribution and for the distribution giving constant radial power production in the reactor core.

General Method of Analysis

In order to assure proper investment for the entire life of one fuel loading of the reactor, it was necessary first of all to make criticality calculations at the hot-burnup condition described previously. The reactor was considered to be at the full-power operating conditions at the end of its life. The reactor poisons considered were: (a) equilibrium concentrations of Xe^{135} and Sm^{149}, and (b) stable fission-product poisons corresponding to approximately 10 percent U^{235} burnup. The poisons were taken to be uniformly distributed over the core volume. This assumption is justified by the results of the investigation of reference 3. The stable poisons were specified as having an average thermal absorption cross section of 75 barns per fuel atom destroyed. This is the value at 0.025-ev energy, and a 1/v variation is assumed. For the hot-burnup condition the uranium content required for reactor criticality was determined for each of the following cases:

I. Uniform U^{235} distribution, 10-centimeter reflector

II. Uniform radial power distribution, 10-centimeter reflector

III. Uniform U^{235} distribution, infinite reflector

IV. Uniform radial power distribution, infinite reflector

For cases I and III, the radial power distribution is also obtained, while for cases II and IV, the uranium distribution is also obtained in the criticality calculations.

2932 At the cold-clean condition, previously described briefly, no poisons were present in the reactor core and the uranium content was larger than at the hot-poisoned condition by the amount of fuel burnup, which was assumed to be 1.3 kilograms. This fuel burnup, which is somewhat less than 10 percent of the fuel investment, corresponds to the amount required for 300,000-kilowatt reactor power output for a total of 100 hours. For each of the cases I to IV, the 1.3 kilograms of U^{235} was distributed over the core volume so that the local fuel burnup is proportional to the local power (or fission-rate) production existing at the hot-burnup condition (considered to be at the end of reactor life). Although the relative local power production actually varies with time, this variation was small for the small burnups herein involved so that negligible error was introduced by distribution of the fuel burnup in this manner. For each of the cases I to IV, two reflector configurations were considered for the startup condition, namely, (a) the normal (unpoisoned) water reflector, and (b) the water reflector incorporating a sleeve of thermal-neutron poison sufficient to make φ_{th} go to zero adjacent to the entire cylindrical boundary of the core.

From the foregoing calculations, the reactivity change from hot-burnup to cold-clean and the reactivity change attainable with a thermally poisoned reflector were obtained for each of cases I to IV.

For comparative purposes, calculations were also made for cases I to IV, cold-clean poisoned-reflector conditions, of the effect of initial loadings limiting the uranium burnup to 0.65 kilograms.

Reactor Calculations and Evaluation of Nuclear Constants

The two-group neutron-diffusion equations applicable to core and reflector in a critical reactor assembly are:

$$\frac{\lambda_{tr,f}}{3}\nabla^2\varphi_f - (\Sigma_{a,f} + \Sigma_{q,f})\varphi_f + k_{th}\,\Sigma_{a,th}\,\varphi_{th} + k_f\,\Sigma_{a,f}\,\varphi_f = 0 \tag{1}$$

$$\frac{\lambda_{tr,th}}{3}\nabla^2\varphi_{th} - \Sigma_{a,th}\,\varphi_{th} + \Sigma_{q,f}\varphi_f = 0 \tag{2}$$

For a fully reflected cylindrical core (with both end and side reflectors), φ_f and φ_{th} are functions of two dimensions, radius r and height z (see fig. 1). Inasmuch as the effect of the side reflector on the reactivity of the reactor assembly is of interest here, the fully reflected assembly can, for this purpose, be suitably approximated by an equivalent reactor core, bare at the ends and reflected at the sides; this approximation leads to separation of the variables r and z, in which case the flux φ is given by the product $\varphi(r)\,\psi(z)$ where $\varphi(r)$ is a function of r only and $\psi(z)$ is a function of z only.

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In the use of this approximation, the half-height $H_c/2$ of the equivalent reactor core is increased above that of the given fully reflected core by an amount equal to the reflector savings, as illustrated in figure 1. Reflector savings for water reflectors around water-moderated cores are presented in reference 4 and are substantially independent of core composition for water-moderated cores that are predominantly thermal.

Inasmuch as the ends are bare for the equivalent reactor core, φ_f and φ_{th} must fall to zero at $z = \pm H_c/2$. If it is assumed that $\varphi = \varphi(r) \cdot \psi(z)$, this condition is satisfied by

$$\psi(z) = A \cos \frac{\pi z}{H_c} \tag{3}$$

and, noting that for cylindrical geometry

$$\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2} \tag{4}$$

equations (1) and (2) reduce to equations in the independent variable r only:

$$\frac{\lambda_{tr,f}}{3}\nabla_r^2\varphi_f - \left(\Sigma_{a,f} + \Sigma_{q,f} + \frac{\lambda_{tr,f}}{3}\frac{\pi^2}{H_c^2}\right)\varphi_f + k_{th}\,\Sigma_{a,th}\,\varphi_{th} + k_f\,\Sigma_{a,f}\,\varphi_f = 0 \tag{5}$$

$$\frac{\lambda_{tr,th}}{3}\nabla_r^2\varphi_{th} - \left(\Sigma_{a,th} + \frac{\lambda_{tr,th}}{3}\frac{\pi^2}{H_c^2}\right)\varphi_{th} + \Sigma_{q,f}\,\varphi_f = 0 \tag{6}$$

where

$$\nabla_r^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r}$$

and where $\varphi_f(r)$ and $\varphi_{th}(r)$ are designated, for convenience, as φ_f and φ_{th}. The terms involving the coefficient π^2/H_c^2 account for the net axial leakage of neutrons in the equivalent reactor core. Hence, if the proper value of H_c is used, it effectively accounts for the axial leakage in a fully reflected core. Equations (5) and (6) apply to either the core or the side reflector by use of the appropriate nuclear constants characteristic of either the core or reflector composition. In the application of equations (5) and (6) for the uniform-radial-power cases (cases II and IV), account was taken of the variations of the fast as well as the thermal parameters with radial position r across the reactor core.

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In the solution of the core and reflector equations, the radial boundary conditions were taken as follows:

(1) For the normal reflector: $\varphi_f = \varphi_{th} = 0$ at the outermost (extrapolated) boundary of the reflector; fast and thermal flux and current continuity were assumed at the core-reflector interface.

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(2) For the reflector incorporating thermal-neutron poison adjacent to the core boundary: $\varphi_f = 0$ at the outermost boundary of the reflector; fast flux and current continuity were assumed at the core-reflector interface; $\varphi_{th} = 0$ at the core boundary. Note that these boundary conditions imply that the fast flux is unaffected by the reflector poison except as indirectly affected by the thermal flux falling to zero at the core boundary.

The two-group equations for core and reflector subject to the foregoing boundary conditions were solved by use of an electrical-analog simulator at the NACA Lewis laboratory. This nuclear-reactor simulator and the general procedure in its use to solve reactor criticality problems have been described in detail in references 1, 5, and 6.

The procedure for evaluating the nuclear constants for use in equations (5) and (6) is described in reference 7. In the evaluation of the constants, use is made of the following definitions:

$$L_f^2 = \frac{\lambda_{tr,f}}{3(\Sigma_{a,f} + \Sigma_{q,f})}$$

$$p_{th} = \frac{\Sigma_{q,f}}{\Sigma_{a,f} + \Sigma_{q,f}}$$

$$k_f = \frac{\nu\Sigma_{F,f}}{\Sigma_{a,f}}$$

$$k_{th} = \frac{\nu \Sigma_{F,th}}{\Sigma_{a,th}}$$

The procedure is patterned after that successfully used in reference 8 to predict the criticality of water-moderated reactors. For the reactors of reference 8, $p_{th} \approx 1$, whereas for the reactors herein considered, $p_{th} \approx 0.80$ to 0.90; hence, the fast-fission contribution should be accounted for. The general procedure of reference 8 is used in accounting for this effect, as well as for the calculations of the cross section values. The procedure is briefly outlined as follows: 2932

$\lambda_{tr,f}$, $\Sigma_{a,f}$, $\Sigma_{F,f}$, p_{th}. - The quantities $\lambda_{tr,f}$, $\Sigma_{a,f}$, $\Sigma_{F,f}$, and p_{th} were obtained by weighting local energywise values according to the energy distribution of neutron flux, as indicated by age theory, in an infinite medium of the same composition. The dependence of this distribution on the fission spectrum is included.

L^2_f. - For water, L^2_f is based on the experimental value of 33 square centimeters at room temperature ($\rho = 1$ g/cc) and is taken as inversely proportional to the square of the water density at higher water temperatures. For the given core composition, this value is increased by 2 square centimeters to account for the 11.6 volume percent of stainless steel in the core.

$\lambda_{tr,th}$. - By use of the method of reference 9 to account for the chemical binding of hydrogen, the experimental values of σ_s for hydrogen are used to calculate the local values of σ_{tr} of hydrogen. The quantity $\lambda_{tr,th}$ is then evaluated by weighting $\lambda_{tr} = \frac{1}{\Sigma N_i \sigma_{tr}{}^i}$ according to the neutron flux in a Maxwellian distribution.

$\Sigma_{a,th}$, $\Sigma_{F,th}$. - The fission poisons are treated separately in the next section. The following description applies, however, for all materials in the reactor excepting Xe^{135} and Sm^{149}. The terms $\Sigma_{a,th}$ and $\Sigma_{F,th}$ are obtained by assuming the local values of $\Sigma_{a,th}$ and $\Sigma_{F,th}$ to obey the 1/v law and by then weighting the local values according to the neutron flux in a Maxwellian distribution. For this variation with energy, $\Sigma_{a,th}$ (or $\Sigma_{F,th}$) equals 0.886 times the value of Σ_a (or Σ_F) corresponding to the most probable energy (kT) of the thermal neutron distribution.

Fission Poisons and Burnup

The equilibrium concentration of Xe^{135} is given by

$$N_{xe} = \frac{F y_{xe}}{\lambda_{xe} + \bar{\sigma}_{xe,th}\,\varphi_{th}} \tag{7}$$

where $\bar{\sigma}_{xe,th}$, obtained from reference 10, is given by weighting local values of σ_{xe} according to the neutron flux in a Maxwellian distribution.

For purposes of calculating poison concentrations, the reactor is assumed to be nearly thermal in which case $F = \Sigma_{F,th}\,\varphi_{th}$ so that equation (7) can be written as

$$N_{xe}\,\bar{\sigma}_{xe,th} = \bar{\Sigma}_{xe,th} = \frac{F y_{xe}}{\dfrac{\lambda_{xe}}{\sigma_{xe,th}} + \dfrac{F}{\Sigma_{F,th}}} \tag{8}$$

The equilibrium concentration of Sm^{149} is given by

$$N_{sm}\,\bar{\sigma}_{sm,th} = \bar{\Sigma}_{sm,th} = \frac{F y_{sm}}{\varphi_{th}} \tag{9}$$

or, for a thermal reactor,

$$\bar{\Sigma}_{sm,th} = y_{sm}\,\Sigma_{F,th} \tag{10}$$

The remaining poisons, which are lumped together, are specified as having an average thermal absorption cross section $\bar{\sigma}_{p,th}$ of 75 barns per fuel atom destroyed at a temperature of 59° F and as following the $1/v$ law. For 10-percent fuel burnup (11.1 percent of the fuel left in the reactor at the end of its life), the absorption is given by

$$\bar{\Sigma}_{p,th} = 0.111\left(\frac{75}{549}\right)\Sigma_{F,th}$$

where 549 is the value of the U^{235} fission cross section at 0.025 ev.

The pertinent constants used to evaluate the foregoing poison cross sections are: $y_{xe} = 0.063$; $\bar{\sigma}_{xe,th} = 2.32\times10^{6}$ barns at 0.052 ev.; $\lambda_{xe} = 2.103\times10^{-5}\ \text{sec}^{-1}$; $y_{sm} = 0.014$; average $F = 2.7\times10^{13}$ fissions per second per cubic centimeter based on 300,000-kilowatt reactor total power output at 200 Mev per fission.

The core and reflector parameters for case I (uniform U^{235} distribution, 10-cm reflector) are tabulated in table II for the cold-clean and hot-burnup conditions. The parameters N_u, p_{th}, k_f, $\Sigma_{u,th}$, and $\Sigma_{F,th}$ vary with uranium concentration while the remaining parameters are essentially constant. The reflector parameters were the same for all cases, differing only for the change in temperature conditions as listed.

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RESULTS AND DISCUSSION

(1) Reactivities and investments. - Table III presents k_{eff} and Δk_{eff} due to reflector poisoning and also the uranium investments for all cases and conditions considered. The reactor is critical ($k_{eff} \approx 1.00$) for the hot-burnup condition for each case. For the cold-clean condition various amounts of excess reactivity are present. For the uniform-uranium cases, k_{eff} is 1.154 for the 10-centimeter reflector and 1.147 for the infinite reflector; the amounts of excess reactivity to be controlled are approximately 0.162 and 0.148, respectively. Similarly, for the uniform power cases (cold-clean) k_{eff} is 1.150 for the 10-centimeter reflector and 1.132 for the infinite reflector, which means excessive reactivities of 0.150 and 0.132, respectively. Since the introduction of thermal-neutron poison in the reflector causes changes of only 0.014 and 0.016 for the uniform-uranium cases, and 0.029 and 0.030 for the uniform-power cases, reflector control is inadequate in this type of reactor. Certain interesting observations can be made, however. Slightly greater control was possible with the better reflector. More important, nearly twice the change in reactivity was found when the fissionable material was distributed for uniform power production as compared to a uniform distribution of fuel. Condition (d) of all cases gives k_{eff} for the cold-clean reactor with a poisoned reflector but for an assumed burnup of 0.65 kilogram instead of 1.3-kilogram burnup as in the previous cases. As expected, k_{eff} is reduced, but the reactor is still supercritical by 9 to 12 percent in the various cases.

The investment of uranium required for a critical assembly is less when distributed uniformly than when distributed for uniform radial power production. For the 10-centimeter reflector thickness, the uranium investment is increased from 16.0 to 21.05 kilograms when the fissionable material is distributed nonuniformly to attain constant radial power production; the corresponding increase is from 15.5 to 18.24 kilograms for the infinite reflector.

(2) Uranium distributions. - In figure 2 are presented the uranium distributions as functions of core radius for cases I through IV in the cold-clean and the hot-burnup conditions (for 1.3-kg burnup); figure 2(a) is for the 10-centimeter reflector (cases I and II) and figure 2(b) is for the infinite reflector (cases III and IV).

The ordinate in figure 2 is $N_u/N_{u,O}$ where N_u is the local uranium concentration and $N_{u,O}$ is the concentration required for the uniform-uranium cases at the hot-burnup condition (case I(c) in fig. 2(a) and case III(c) in fig. 2(b)). Figure 2 shows the typically high uranium concentrations near the core-reflector interface relative to the concentrations in the central portions of the core required to attain uniform radial power production. For the case of uniform uranium distribution in the hot-burnup condition, the fuel burnup varies over the reactor core volume; hence, the uranium loading, of necessity, must vary over the core volume in the cold-clean condition. This variation, although slight for the burnup assumed, is evident in figure 2. For the cases of uniform power, the burnup is essentially constant over the core volume; hence, the uranium loading for the cold-clean condition is greater, by a constant amount, over that for the hot-burnup condition. The total uranium requirements for the uniform-power cases are 31.6 and 17.7 percent higher than for the corresponding uniform-uranium cases for the 10-centimeter and infinite reflector, respectively.

(3) Power distributions. - The power-production distributions within the reactor core are presented in figure 3 as plots of H/H_{max} versus radius r, where H is the local power production and H_{max} is the maximum power production. The ratio of the average to the maximum power density H_{av}/H_{max} is also indicated for each of the cases treated. Figure 3(a) is for the 10-centimeter reflector (cases I and II) and figure 3(b) is for the infinite reflector (cases III and IV). For each case, the power distribution and average- to maximum-power production is given for: (a) the cold-clean condition with unpoisoned reflector, (b) the cold-clean condition with poisoned reflector, and (c) the hot-burnup condition.

Figure 3 illustrates the large spatial variations in power obtained for uniform uranium loading; for example, in figure 3(a) for case I(c), the power drops to 37.5 percent of maximum near the reflector. Comparison of the hot-burnup and the cold-clean unpoisoned-reflector conditions for each case gives an indication of the power variations with fuel burnup. In figure 3(a), comparison of II(a) and II(c) shows that for uniform power in the hot-burnup condition, the power distribution in the cold-clean condition is distorted resulting in $H/H_{max} = 0.83$ near the reflector and = 0.93 at the center of the core. In figure 3(b), case IV(a) shows a more severe power distortion resulting in $H/H_{max} = 0.76$ near the reflector.

Figure 3 shows the distortions in power distribution caused by the use of reflector poisoning (cases I(b), II(b), III(b), and IV(b) in figs. 3(a) and 3(b)). For the uniform-power cases (note that uniform power is achieved for hot-burnup condition with unpoisoned reflector), the distorted power distribution due to reflector poisoning is still more favorable, insofar as total power output for limiting heat flux is concerned, than the power distributions for any of the conditions of the uniform-uranium cases. To illustrate, in figure 3(a), $H_{av}/H_{max} = 0.82$ for case II(b) compared to 0.61 for case I(c). Case II(b) is for the poisoned reflector, whereas case I(c) is for the unpoisoned reflector. The same general result is indicated in figure 3(b) wherein $H_{av}/H_{max} = 0.79$ for case IV(b) compared to 0.65 for case III(c). It appears, then, that if the uranium is distributed nonuniformly to achieve uniform power during normal reactor operation with unpoisoned reflector, the distorted power distribution resulting from the use of reflector poison is nevertheless more favorable than that for the uniform-uranium case with or without reflector poison. 2923

CONCLUSIONS

Nonuniform uranium loading in the core of a large thermal reactor (2.5-ft square cylinder with water moderation; resonance escape probability, ~ 0.90) to attain uniform radial power production resulted in a doubling of the reflector control effectiveness over that obtainable for uniform uranium loading. A smaller further increase in effectiveness was also obtained by using a more efficient reflector. However, the reactivity changes were still much too small compared to the amount required. For the best case, the change in over-all neutron multiplication factor Δk_{eff} was 0.03 as compared to the 0.132 required. The uranium investments required for the uniform-power cases were 31.6 and 17.7 percent higher than that for the comparable uniform uranium cases. The power distribution was better for the cases with the uranium distributed for uniform power, even after being distorted by the reflector poison (ratio of average to maximum power density in reactor $H_{av}/H_{max} = 0.82$) than it was for the uniform uranium case without reflector poison ($H_{av}/H_{max} = 0.61$).

Although the increase in reflector control effectiveness was not sufficient to be of use for the reactor considered herein, it may provide the required margin to permit use of reflector control for a smaller, more heavily loaded reactor employing a more efficient reflector.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, September 9, 1953

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TABLE I. - CORE AND REFLECTOR COMPOSITIONS

Operating condition	Material	Core				Reflector			
		Density, g/cc	Volume, percent	Kind of nuclei	Number of nuclei per cc of core	Density, g/cc	Volume, percent	Kind of nuclei	Number of nuclei per cc
Hot dirty reactor	H_2O	0.71	88.4	H	4.220×10^{22}	0.83	100	H	5.552×10^{22}
$T = 620^\circ$ F, $E_{th} = 0.052$ ev in core				O	2.110×10^{28}			O	2.776×10^{22}
$T = 480^\circ$ F, $E_{th} = 0.045$ ev in reflector	AISI type 347	8.03	11.6	Fe	6.854×10^{21}				
				Ni	9.057×10^{20}				
				Cr	1.840×10^{21}				
				Nb	5.716×10^{19}				
				Mn	1.933×10^{20}				
Cold clean reactor	H_2O	1.00	88.4	H	5.94×10^{22}	1.00	100	H	6.688×10^{22}
$T = 59^\circ$ F, $E_{th} = 0.025$ ev in core				O	2.97×10^{22}			O	3.344×10^{22}
$T = 59^\circ$ F, $E_{th} = 0.025$ ev in reflector	AISI type 347	8.03	11.6	Fe	6.854×10^{21}				
				Ni	9.057×10^{20}				
				Cr	1.840×10^{21}				
				Nb	5.716×10^{19}				
				Mn	1.933×10^{20}				

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TABLE II. - TWO-GROUP THEORY REACTOR CONSTANTS FOR

CASE I (UNIFORM URANIUM LOADING, 10-CM REFLECTOR)

(a) Core.

Constant	Reactor condition	
	Hot-burnup	Cold-clean (for 1.3-kg burnup)
N_u*	11.80×10^{19}	12.76×10^{19}
p_{th}*	.8696	.8762
k_f*	1.290	1.279
π^2/H_c^2	.001296	.001296
$\lambda_{tr,f}$	3.909	2.922
L^2_f	69.4	35.0
$\lambda_{tr,th}$	.9018	.5696
$\Sigma^M_{a,th}$	.02609	.0427
$\Sigma_{u,th}$*	.04711	.0735
$\Sigma^T_{p,th}$	.00363	----------
$\Sigma_{F,th}$*	.03979	.0621

(b) Reflector.

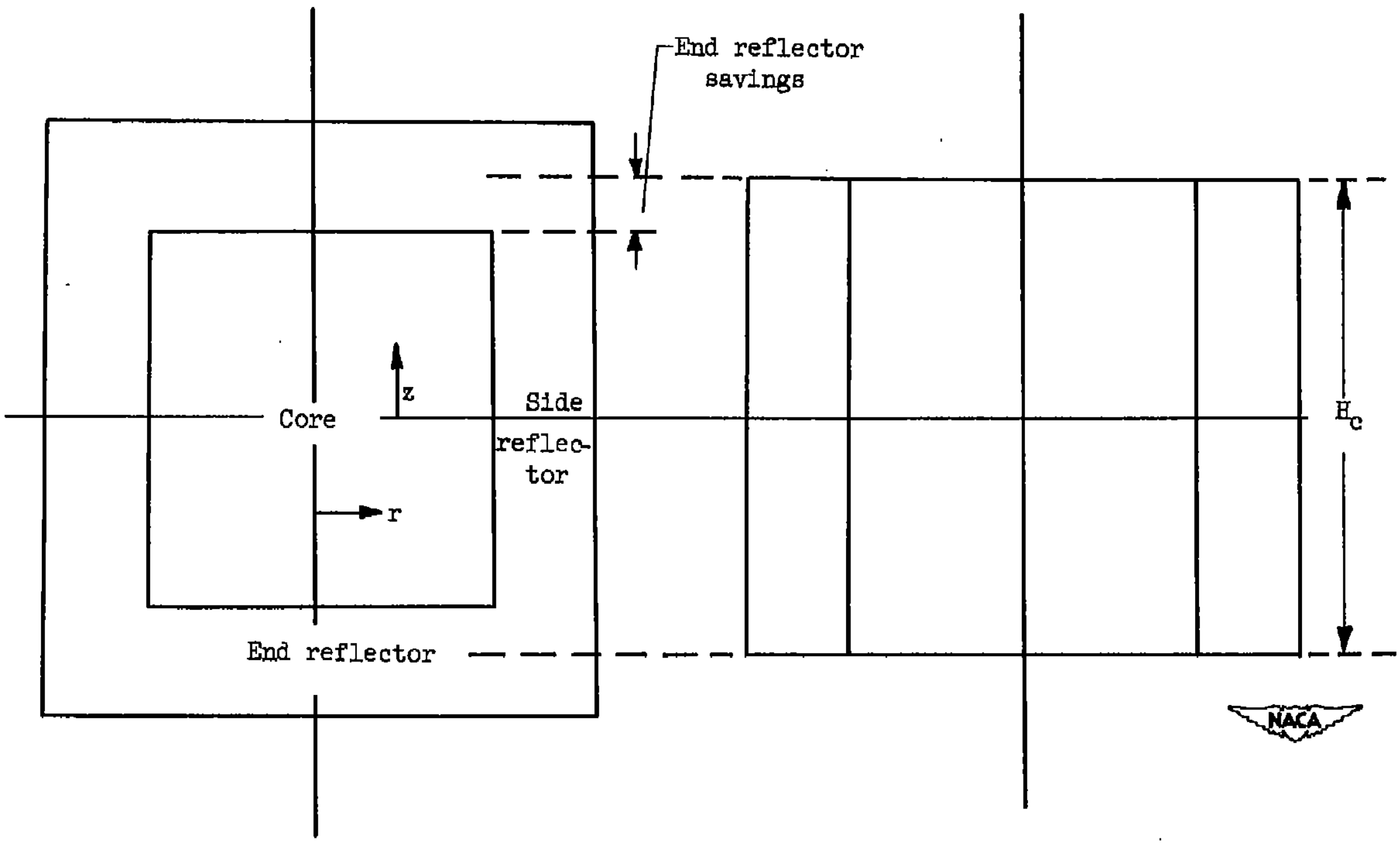
L^2_f	47.9	33
$\lambda_{tr,f}$	4.13	3.43
$\Sigma_{a,f}$	.02874	.03465
p_{th}	.95 (assumed)	.95
L_{th}^2	13.10	8.3
$\lambda_{tr,th}$	.4747	.426
$\Sigma_{a,th}$	.01208	.01711

*Representative values applying only to case I. All other parameters are the same for all four cases.

TABLE III. - REACTIVITY CHANGES DUE TO REFLECTOR POISONING (REACTOR CRITICAL AT HOT-BURNUP CONDITION, REFLECTOR POISONING INTRODUCED IN COLD-CLEAN CONDITION)

(a) Reflector thickness, 10 centimeters.

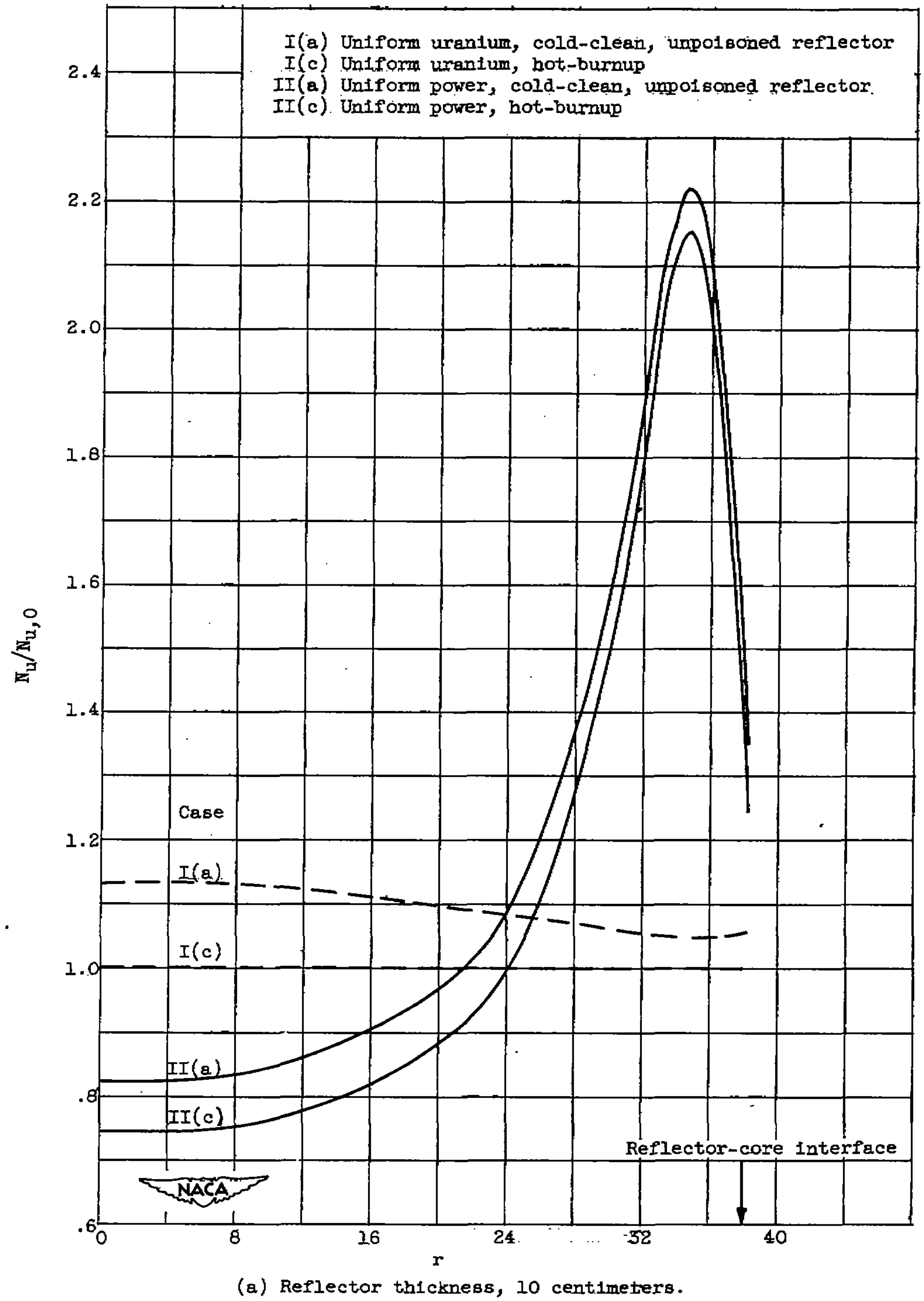
Designation	Case	Condition	U-235 content, kg	k_{eff}	Δk_{eff} due to reflector poison
I(c)	Uniform U	Hot-burnup	16.0	0.992	
I(a)	Uniform U	Cold-clean unpoisoned-reflector	17.3	1.154	0.014
I(b)	Uniform U	Cold-clean poisoned-reflector	17.3	1.140	
II(c)	Uniform power	Hot-burnup	21.05	1.000	
II(a)	Uniform power	Cold-clean unpoisoned-reflector	22.35	1.150	.029
II(b)	Uniform power	Cold-clean poisoned-reflector	22.35	1.121	
I(d)	Uniform U	Cold-clean poisoned-reflector	16.65	1.122	
II(d)	Uniform power	Cold-clean poisoned-reflector	21.70	1.107	
(b) Reflector thickness, infinite.					
III(c)	Uniform U	Hot-burnup	15.5	0.9986	
III(a)	Uniform U	Cold-clean unpoisoned-reflector	16.8	1.147	0.016
III(b)	Uniform U	Cold-clean poisoned-reflector	16.8	1.131	
IV(c)	Uniform power	Hot-burnup	18.24	1.000	
IV(a)	Uniform power	Cold-clean unpoisoned-reflector	19.54	1.132	.030
IV(b)	Uniform power	Cold-clean poisoned-reflector	19.54	1.102	
III(d)	Uniform U	Cold-clean poisoned-reflector	16.15	1.114	
IV(d)	Uniform power	Cold-clean poisoned-reflector	18.89	1.086	



Fully reflected reactor core

Equivalent core with bare ends

Figure 1. - Conversion of fully reflected core to an equivalent core with bare ends by application of end reflector savings.



(a) Reflector thickness, 10 centimeters.

Figure 2. - Variation in uranium loading for hot-burnup and cold-clean conditions for cases where uranium is adjusted to give uniform loading and uniform power in hot-burnup condition.

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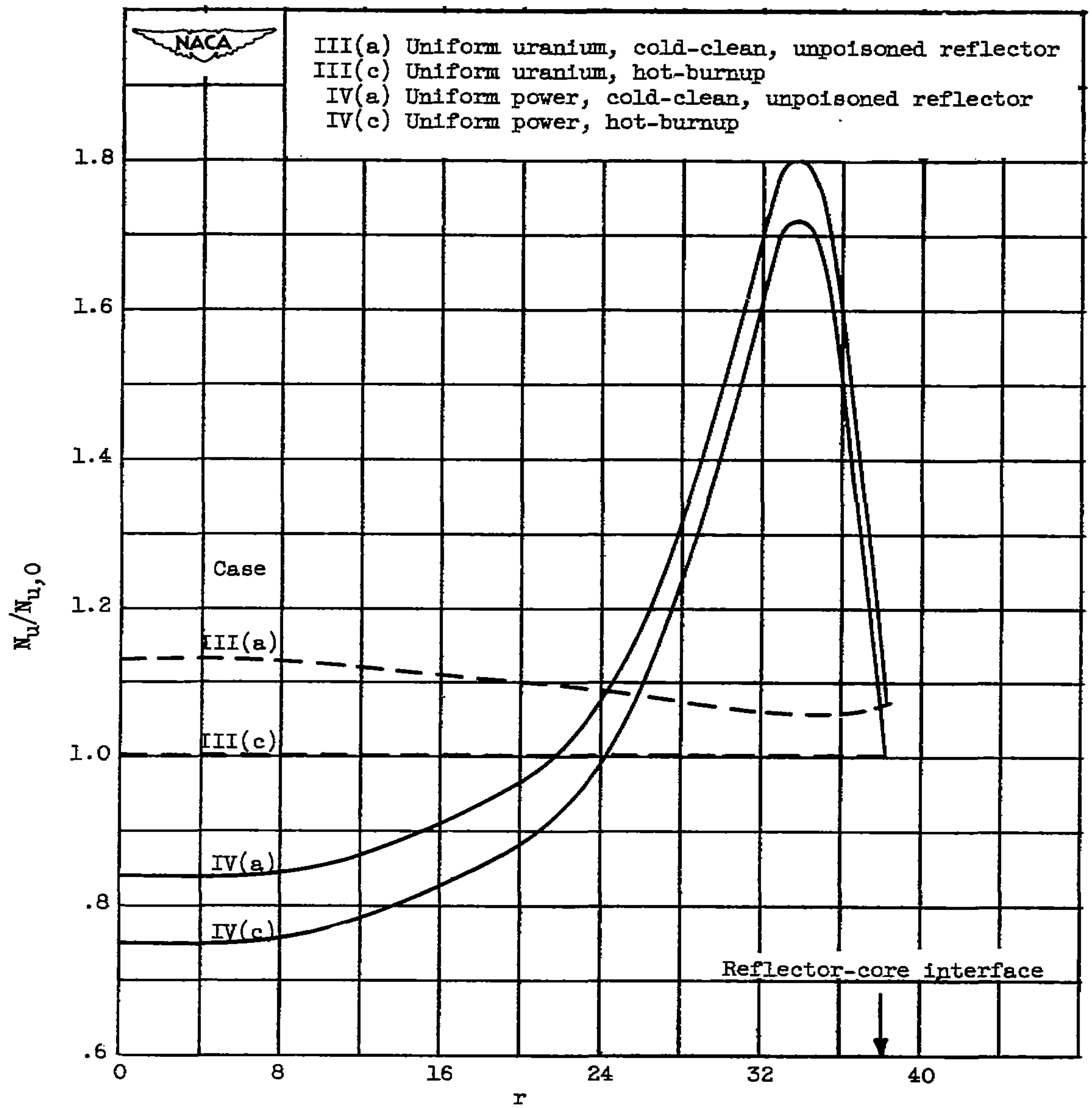
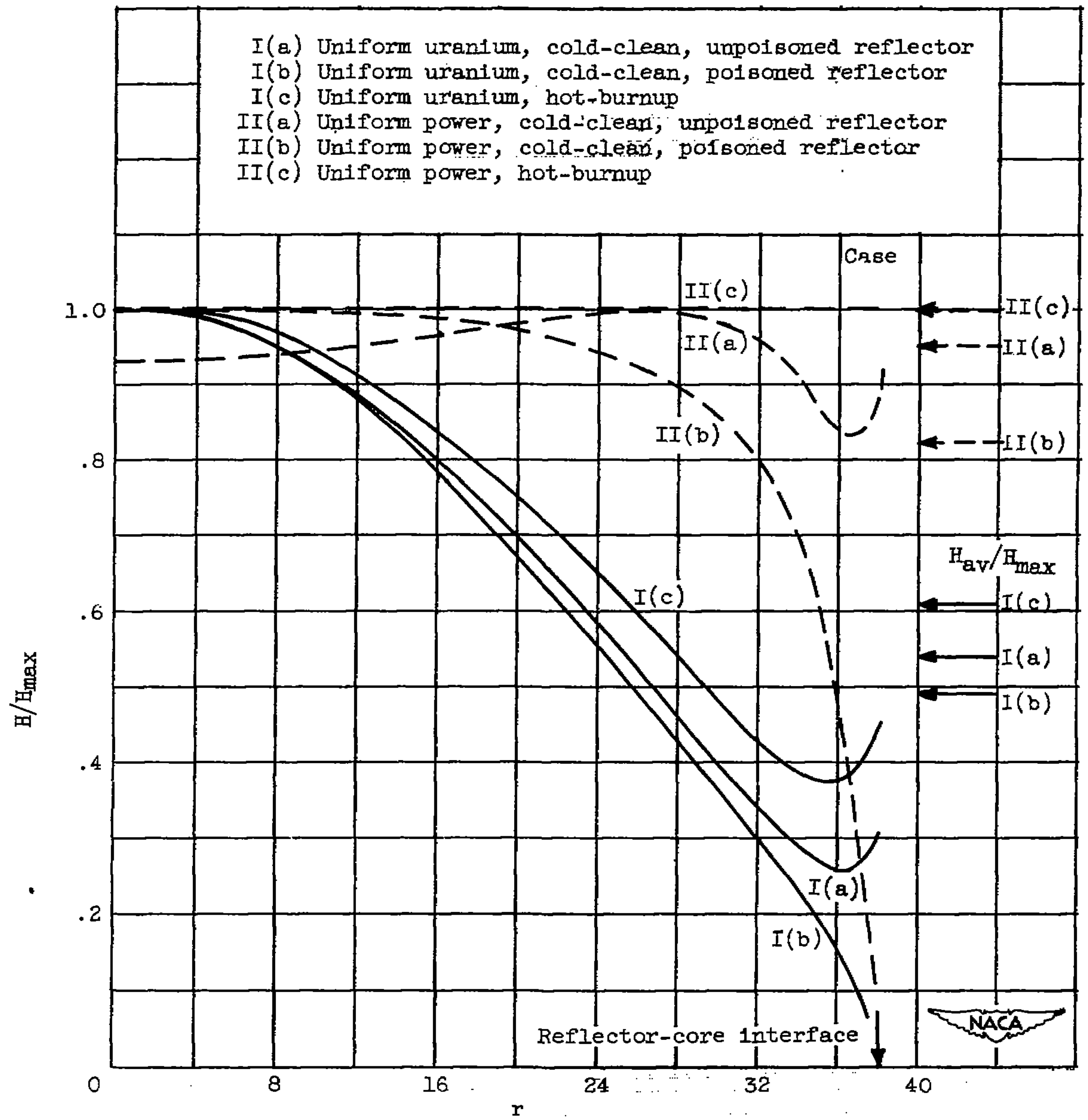


(b) Infinite water reflector.

Figure 2. - Concluded. Variation in uranium loading for hot-burnup and cold-clean conditions for cases where uranium is adjusted to give uniform loading and uniform power in hot-burnup condition.



(a) Reflector thickness, 10 centimeters.

Figure 3. - Variation in power production and ratio of average to maximum power density over reactor volume for cases where uranium is adjusted to give uniform loading and uniform power in hot-burnup condition.

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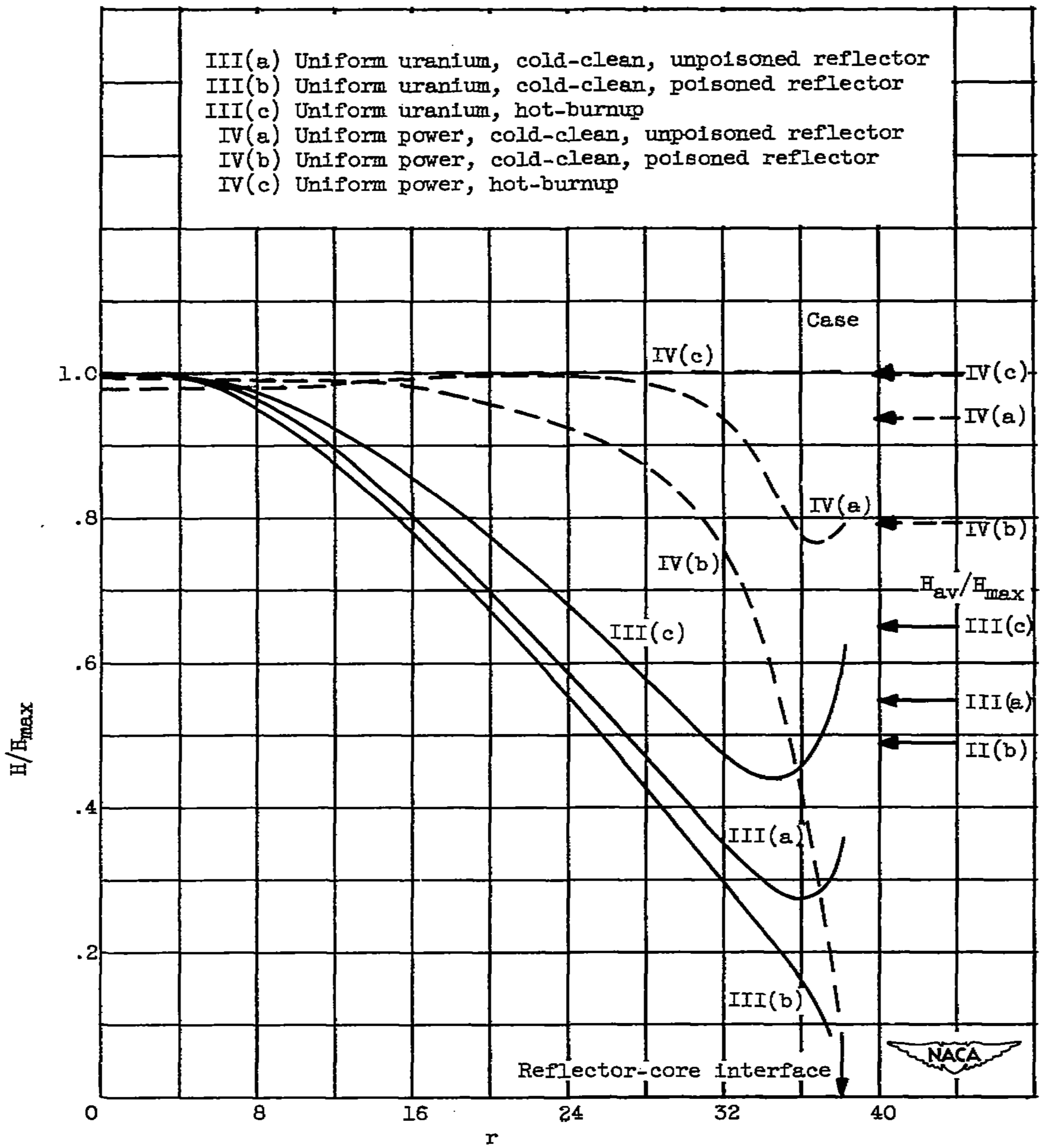

(b) Infinite water reflector.

Figure 3. - Concluded. Variation in power production and ratio of average to maximum power density over reactor volume for cases where uranium is adjusted to give uniform loading and uniform power in hot-burnup condition.