[redacted]

SPECIAL RE-REVIEW
FINAL DETERMINATION
UNCLASSIFIED, DATE: 7/30/79

[redacted]

60?

VERIFIED UNCLASSIFIED
NA JUN 1 2 1979
LMR 7/30/79

[redacted]

C. 2

[redacted]

[redacted]

Crash document

Classification changed to UNCLASSIFIED
by authority of the U. S. Atomic Energy Commission,
Per Frank Hoyt, LASL 2-2-73
By REPORT LIBRARY Dan Bean 7-30-74

[redacted]

PUBLICLY RELEASABLE
Per E. M. Sandoval, FSS-16 Date: 8/2/85
By Marlene Lujan CIC-14 Date: 8-1-96

UNCLASSIFIED
UNCLASSIFIED

LA - 602

This [redacted] es.

August 14, 1946

This document contains 20 pages.

IGNITION OF THE ATMOSPHERE WITH NUCLEAR BOMBS

WORK DONE BY:

REPORT WRITTEN BY:

E. J. Konopinski
C. Marvin
E. Teller

[redacted] prohibited by law.

[redacted]

ABSTRACT

It is shown that, whatever the temperature to which a section of the atmosphere may be heated, no self-propagating chain of nuclear reactions is likely to be started. The energy losses to radiation always overcompensate the gains due to the reactions. This is true even with rather extravagant assumptions concerning the reactivity of the nitrogen nuclei of the air. The only disquieting feature is that the "safety factor", i.e. the ratio of losses to gains of energy, decreases rapidly with initial temperature, and descends to a value of only about 1.6 just beyond a 10-Mev temperature. It is impossible to reach such temperatures unless fission bombs or thermonuclear bombs are used which greatly exceed the bombs now under consideration. But even if bombs of the required volume (i.e., greater than 1000 cubic meters) are employed, energy transfer from electrons to light quanta by Compton scattering will provide a further safety factor and will make a chain reaction in air impossible.

[redacted]

IGNITION OF THE ATMOSPHERE WITH NUCLEAR BOMBS

1. Introduction

The detonation of a fission or thermonuclear bomb produces a high temperature which will stimulate the reaction of atomic nuclei of the air with each other. If an ignition point exists and is surpassed, the thermonuclear reaction may be propagated to all parts of the atmosphere.

Propagation of the reaction demands that the energy production in each newly entered region exceed the losses from that region. The energy appears in the form of the kinetic energy of particles which are products of exoergic nuclear reactions. The product particles, through collisions, share their energy with the particles of the air and help maintain the temperature. On the other hand, the share of the energy given the electrons is rapidly radiated away. This constitutes the chief energy loss. The radiation cannot help to maintain temperature because of the great transparency of air, and because, even if the heated volume is great enough to "contain" the radiation, the heat capacity of space for radiation is so great that the energy produced in the reaction is many orders of magnitude too small to maintain the needed radiation temperature.

On a first evaluation of the danger of igniting the atmosphere, one can assume that the reaction product particles do not effectually disperse their energy but deposit it where they are produced. Then one can compare this rate of deposition with the radiation rate. The temperature, if such exists, at which the energy production rate equals the radiative loss rate will be the temperature of ignition. Because of the uncertainties in the knowledge of these processes, the policy should be adopted of exaggerating the dangers at any point which appears at all questionable. For this reason, it should be assumed that since the rate of energy transfer from product particles to nuclei

[redacted]

is effected with an unknown cross section, and since the transfer between nuclei which have comparable mass is usually more rapid than the transfer to electrons, all the energy goes first to establishing a nuclear temperature. The simultaneous temperature of the electrons will be determined by the balance of transfer rate to electrons and radiation rate by the electrons. This temperature may be considerably lower than the nuclear temperature and thus increase the danger of ignition by inhibiting the radiation loss rate.

The preceding considerations will yield an evaluation of the margin of safety as a function of the temperature of the atmosphere. A final section will be devoted to the behavior of a hot air mass of finite volume and to the heating which a fission or thermonuclear bomb may actually be able to supply.

2. THE ENERGY PRODUCTION

The nuclear reactions most to be feared in air are the reactions of pairs of nitrogen nuclei. Other notable constituents of the atmosphere, oxygen, carbon and rare gas nuclei, are much more stable than nitrogen, yielding comparatively little energy. There is perhaps one other nucleus that should be given careful attention: the proton. It is ordinarily much less abundant in the atmosphere than is nitrogen, but clouds of steam raised over the oceans by intense heating, may radically alter that situation. This danger will be given attention after the discussion of the reactions of nitrogen nuclei with each other has been completed.

The nitrogen-nitrogen reactions in which sufficient energy is produced to enable the product particles to surmount each others Coulomb barriers are the following:

$$N_7^{14} + N_7^{14} \rightarrow Si_{14}^{28*} \rightarrow Si_{14}^{28} + \gamma + 26.7 \text{ Mev.}$$
$$\rightarrow Si_{14}^{27} + n + 10.6 \text{ Mev. } (B \approx 0)$$
$$\rightarrow Al_{13}^{27} + p + 16.0 \text{ Mev. } (B \approx 3.7 \text{ Mev})$$
$$\rightarrow Mg_{12}^{24} + \alpha + 17.7 \text{ Mev. } (B \approx 7 \text{ Mev})$$
$$\rightarrow O_8^{16} + C_6^{12} + 10.6 \text{ Mev. } (B \approx 14 \text{ Mev})$$

In parenthesis following the reactions are given the heights of the Coulomb barriers of the product particles. In accord with the policy of adopting the most dangerous assumptions, it will be assumed that 17.7 Mev per reaction is released, as is characteristic of the alpha emission. (The capture of nitrogen by nitrogen, the first reaction listed, is certainly infrequent compared to particle emission, as reactions of this type always are. Moreover, energy in the form of γ-rays will be unavailable for carrying on the chain.)

The cross section for nitrogen encounters is not known from observation. If the geometric cross section is adopted, and a reaction attributed to every encounter, then certainly the reaction cross section will be exaggerated. The geometric cross section amounts to just $\sigma_k = 2$ barns. The assumption that this is a constant cross section for all energies will be referred to as the "constant" assumption and will be denoted by the subscript "k". Calculation will also be undertaken with the assumption that the geometric cross section σ_k is reached only at energies surpassing the barrier height, $B \approx 8.6$ Mev, between nitrogen nuclei. For relative energies lower than this barrier height, a cross section proportional to the Gamow penetration probability is assumed.* The subscript G will denote this alternative set of assumptions:

$$\sigma_G = \sigma_0 \quad \text{EXP}\left(- 98 \pi e^2/\hbar v \right), \; E < 8.6 \text{ Mev.}$$

$$= \sigma_k = 2 \text{ barns} \qquad , \; E > 8.6 \text{ Mev.}$$

*Actually some reactions, for instance $N^{14} + N^{14} \rightarrow C^{12} + O^{16}$, may proceed with a larger cross section than given by the Gamow factor. This is due to a process similar to the one which Philipps and Oppenheimer discussed in the case of deuteron bombardment. When the two nitrogen nuclei have approached sufficiently one of them may split off an H^2 nucleus which attaches itself to the other N^{14} and forms O^{16}.

[redacted]

The exponential is the Gamow factor, v being the relative velocity of the nitrogen nuclei. E is the relative energy, $E = (1/2)\mu v^2$, as determined with the reduced mass $\mu =$ one-half the nitrogen mass. The constant σ_o is to be determined so that σ_G becomes 2 barns at $E = 8.6$ Mev. This gives $\sigma_o = 2(10)^{19}$ barns.

The rate at which the nuclear reactions will produce energy is

$$dE/dt = (1/2) N \overline{\sigma V} Q$$

in energy units per second per nitrogen nucleus. N is the atomic density of nitrogen in air, $N \sim 4(10)^{19}$ nuclei/cm^3. By $\overline{\sigma V}$ is meant an average over the Maxwell distribution of the product of cross section and relative velocity:

$$\overline{\sigma V} = 4\pi \left(\frac{\mu}{2\pi T}\right)^{3/2} \int_0^{\infty} e^{-\mu v^2/2T} \sigma v^3 dv$$

of T is written for kx temperature. If σ is simply 2 barns at all energies,

$$\overline{(\sigma V)}_k = 2 \sqrt{8T/\pi\mu} \text{ barns-cm/sec.}$$

For great-enough temperatures also

$$\overline{(\sigma V)}_G \approx 2 \sqrt{8T/\pi\mu} \text{ barns-cm/sec} \quad (T \gg 8.6 \text{ Mev})$$

At low temperatures, with T in Mev,

$$\overline{(\sigma V)}_G \approx 1.64(10)^{30} \quad e^{-49.6/T^{1/3}} \text{ barns-cm/sec} \quad (T \lesssim 0.[illegible] \text{ Mev})$$

Results for intermediate temperatures were obtained by numerical integration. The contribution of the collisions with energy greater than the barrier height can be given analytically as

$$\overline{(\sigma V)}'_G = 2 \sqrt{8T/\pi\mu} \; (1 + B/T) \; e^{-B/T} \text{ barn - cm/sec}$$

This part by itself constitutes a lower estimate for $\overline{(\sigma V)}_G$ an upper estimate

 [redacted]

is $(\overline{\sigma V})_k = 2\sqrt{8T/\pi\mu}$. The upper and lower estimates coincide closely when the factor $(1 + B/T)\ e^{-B/T} \approx 1$. For example:

$$(1 + B/T)\ e^{-B/T} \approx 0.76 \quad \text{for} \quad T = 9 \text{ Mev}$$

$$\approx 0.89 \quad \text{for} \quad T = 15 \text{ Mev}$$

Using the above results for $(\overline{\sigma V})$, one obtains the energy production rate per nitrogen nucleus:

$$(dE/dt)_k = 0.42 \sqrt{T} \quad (\text{Mev}/\mu\text{sec}) \quad T \text{ in Mev.}$$

with the "constant cross section" assumption. This is also the high-temperature asymptote in the case of the Gamow-factor assumption. For low temperatures, the latter assumption yields:

$$(dE/dt)_G \approx 5.8(10)^{20}\ e^{-49.6/T^{1/3}} \quad (\text{Mev}/\mu\text{sec}) \quad (T \text{ Mev} \lesssim 0.3 \text{ Mev.})$$

Fig. 1 exhibits the variation of the production rate with temperature for the two assumptions.

The possible contributions by reactions of protons with nitrogen will now be discussed. The only ones of these yielding enough energy to allow the product particles to surmount the Coulomb barrier are:

$$N_7^{14} + p \rightarrow C_6^{11} + \alpha + 3.0 \text{ Mev} \quad (B \approx 2.3 \text{ Mev})$$

$$N_7^{15} + p \rightarrow O_8^{15} + n + 3.5 \text{ Mev} \quad (B = 0)$$

The small abundance of N^{15} weighs heavily against the second of these reactions. The cross section of a proton against nitrogen at high energies cannot exceed the 2 barns assumed for N + N, since the geometrical cross section now is expected to be about 1 barn. The geometrical cross section should persist down to an energy at which the proton wave-length is of the order of the nuclear

 [redacted]

radius of nitrogen. This energy is about 1 Mev. The proton-nitrogen barrier extends up to about 1.6 Mev. Accordingly, the cross section of the proton reactions* is never as large as that assumed here for the N + N reaction. In addition, the energy yield from the proton reactions is only about an eighth that assumed for N + N. These factors, combined with the probable low abundance of protons, makes it highly unlikely that the protons are at all as dangerous as the assumed nitrogen-nitrogen reactions.

There remains the possibility that the products of the N + N reactions will themselves react with fresh N nuclei and contribute to the energy gains. This possibility is enhanced during the period in which the primary product particles have not yet lost all the energy with which they are produced. On the other hand, the particles are produced in greatly exoergic reactions, which means that they themselves are very stable nuclei having very little energy to contribute to fresh reactions. The magnitude of the energy release in such secondary reactions will be of the same order as for the proton reactions discussed in the preceding paragraph. As a matter of fact, one of the most prominent of the primary products are protons. The arguments of the preceding paragraph, which indicated that the proton reactions cannot add significantly to the energy production attributed to the N + N reactions, are valid also here. One has available also these additional facts: the cross section of nitrogen for neutrons and for alpha particles (both types of particles are also products of the primary reactions) have been measured up to energies of ~ 1.7 Mev. The results show widely spaced resonances which even at peak value are only of the order of an eighth of a barn. This is much less than the two barns attributed to the primary N + N process.

* N + p cross sections should not differ much from N + n cross sections, which have been measured up to ~ 1.7 Mev. The measurements indicate resonances in the cross section which even at peak value are only of the order of an eighth of a barn.

3. THE ENERGY LOSSES

The main energy loss is due to Bremsstrahlung by the electrons, which has the rate:

$$-(dE/dt)_B = (16/3)\ \ NZ\ \frac{Z^2 e^6}{m\,c^3\,\hbar}\ \ \overline{v(1+E/mc^2)}$$

energy units per second per nitrogen nucleus $Z = 7$, the atomic number of nitrogen. The average indicated in $\overline{v(1+E/mc^2)}$ is to be carried out over the relativistic Maxwell distribution, in general. $(1+E/mc^2)$ is an approximate* relativistic correction factor, E being the kinetic energy of the electron. For low enough temperature

$$\overline{v\ (1+E/mc^2)} = \sqrt{3T/\pi m}\ , \quad \text{if } T \ll mc^2.$$

$$-(dE/dt)_B = 1.7\ \sqrt{T}\quad \text{Mev}/\mu\text{sec}\quad (T \text{ in Mev} \ll 1/2 \text{ Mev})$$

In general,

$$\overline{v(1+E/mc^2)} = \frac{4c}{\pi}\ \frac{[1+3\theta+3\theta^2]\qquad e^{-1/\theta}}{(i/\theta)\ H_o^{(1)}\ (i/\theta)\ -2H_o^{(1)}\ (i/\theta)}$$

in which $\theta = T/mc^2$ and $H_o^{(1)}$, $H_1^{(1)}$ are Hankel functions of the first kind, of zero and first order, respectively. The Bremsstrahlung rate is shown in Fig. 1, as a function of the electron temperature. A distinction is made here between electron and nuclear temperatures as can be seen by comparing the scales, which put the corresponding electron and nuclear temperature at the same abscissa.

The electron temperature may be expected to be lower than the nuclear temperature for the following reason. The energy produced by the nuclear reactions

---

* The correct formula gives a more rapid increase of radiation with energy than given here. The added radiation is difficult to take into account, especially since the exact amount depends on screening effects. (Heitler, Quantum Theory of Radiation, p.172). In any case, the additional radiation is negligible until the electron temperature surpasses 0.7 Mev. But it will be seen that such electron temperatures cannot be expected until nuclear temperatures ≳10 Mev are reached. [redacted]

is in the form of kinetic energy of nuclear particles, aluminum nuclei and protons, for example. Since energy interchanges are much more rapid between particles of comparable mass, the atomic nuclei will tend first to share the energy with each other, establishing a nuclear temperature. Somewhat belatedly, the electrons receive energy which they radiate. The electron temperature for a given nuclear temperature is determined by the balance of the energy transfer from nuclei to electrons with the radiation rate of the electrons. Actually, some energy is transferred directly by the fast reaction product particles to the electrons but it will be in accord with the policy set down to neglect this, since energy given to electrons is radiated and made unavailable for propagating the reaction.

The rate at which the nitrogen nuclei transfer energy to electrons is given by:

$$(dE/dt)_T = 4\pi N \quad (Z^3 e^4/M) \quad (16 + \ln \; T_e) \quad \frac{T_n - T_e}{T_e} \qquad \overline{(1/v)}$$

Here M is the nitrogen nuclear mass and T_n, T_e are respectively nuclear and electron temperatures in Mev. $\overline{(1/v)}$ is the inverse of the electron velocity averaged over a Maxwell distribution of temperature T_e. For low temperatures,

$$\overline{(1/v)} = \sqrt{2m/\pi T_e} \quad , \quad (\; T_e \ll 1/2 \text{ Mev})$$

For higher temperatures, the relativistic Maxwell distribution must be used, giving:

$$\overline{(1/v)} = (1/c)\,(2/\pi\theta)\,\frac{\left[1 + 2\theta + 2\theta^2\right] \quad e^{-1/\theta}}{\left[(i/\theta)H_0^{(1)}(i/\theta) - 2H_1^{(1)}(i/\theta)\right]} \qquad \theta = T_e/mc^2 = T_e/0.511$$

The nuclear and electron temperatures which will co-exist will be given by the equation of the transfer rate to the Bremsstrahlung rate. This yields:

$$T_n - T_e = 317 \left(\frac{1 + 3\theta + 3\theta^2}{1 + 2\theta + 2\theta^2}\right) \frac{T_e^2}{16 + \ln T_e} \qquad \text{Mev}$$

Fig. 2 shows the electron temperature as a function of nuclear temperature. This sets the scale of electron temperatures to be used with the uniform nuclear temperature scale in Fig. 1.

The "safety factor" as defined by

$$S = \left| \frac{\partial E}{\partial t} \right|_B \Big/ \left(\frac{\partial E}{\partial t} \right)_G$$

is plotted in Fig. 3. It has a flat minimum in the neighborhood of 100 Mev, nuclear temperature. Beyond that point the production increases only as $\sim\sqrt{T_n}$ whereas the radiation increases as $\sim T_e^{3/2}$ or T_e with T_e increasing about as $T_n^{1/2}$. Accordingly, the present calculations indicate that no ignition point exists. On the other hand the margin of safety becomes only ~ 1.6. It seems desirable to obtain a better experimental knowledge of the reaction cross section even though termperatures approaching 10 Mev seem hardly impossible.

4. Bomb Heating In Air

The temperature to which air can be heated by a bomb depends on the volume of air to be heated. One can seek to estimate the size of this volume by examining the mechanism of energy transfer from bomb to air. It will be sufficient, and much less difficult, to discuss the possibilities of heating the minimum volume which must be brought up to a high temperature in order to insure propagation of the reaction.

The heating of too small a volume will add enormously to the drains on the energy, because of energy transfer to neighboring volumes. The chief agents on this transfer are the product particles themselves, which start in possession of all the produced energy, then disperse it widely. The product particles which will be first assumed to have all the energy are the 15-Mev alpha particles. No particle produced in air is more energetic than they.

The rate of energy loss, per cm of path, by particles of charge ze and mass M, to the electrons of the air at temperature T_e is:

[redacted]

[redacted]

$$-\frac{dE}{dx} = \frac{4\sqrt{\pi}\ N_e\ z^2 e^4}{\sqrt{E\ T_e}} \sqrt{\frac{m}{M}} \left(\frac{E}{(3/2)\ T_e} - 1\right) (16 + \ln T_e)$$

$N_e = 7N$ is the electron density in the air. This corresponds to the "energy-loss cross section" per air atom:

$$\sigma_E = \frac{1}{NE}\left|\frac{dE}{dx}\right| = 0.032\ \frac{E - (3/2)\ T_e}{(ET_e)^{3/2}}\ (16 + \ln T_e)\ \text{barns},\ (T_e,\ E \text{ in Mev})$$

This has a maximum for $E = (9/2)\ T_e$ at which

$$\sigma_{E_{max.}} = 0.01\ \frac{16 + \ln\ T_e}{T_e^{\ 2}}\ \text{barns}\ \ (T_e \text{ in Mev})$$

At $T_e = 0.4$ Mev, which is the least electron temperature ($T_n \approx 10$ Mev) at which the safety factor has its low value, $\sigma_E < 1$ barn.

The rate of energy loss of the alpha particles to the air nuclei through Coulomb collisions is given by the "cross section":

$$\sigma_n = (2\pi^2 z^2 e^4/E^2)\ (M/M_n)\ (15 + \ln E) = 7.3\ \left[(15 + \ln E)/E^2\right]\ \text{barns},\ (E \text{ in Mev})$$

This formula is good only as long as the alpha particle is more energetic than the nitrogen nuclei. The value of σ_n drops rather suddenly when $E \ll T_n$. Its value will never be more than

$$\sigma_n \approx 7.3\ (15 + \ln\ T_n)/T_n^{\ 2}\ \ \text{barns}\ \ (= 1.2 \text{ barns for } T_n = 10 \text{ Mev})$$

Thus, through Coulomb interactions alone the product alpha particle loses energy with an energy loss cross section of no more than about 2 barns.

The purely nuclear scattering of alphas by nitrogen is unknown. The geometrical cross section is only about 1.3 barns. The concern is with energetic-enough collisions for the geometrical cross section to have significance. To be safe, however, we assume that 1.3 barns is the energy-loss cross section, i.e., that it will give collisions in which practically all the alpha energy is given up. Actually, of course, only about [illegible] the energy is given up per collision.

[redacted]

UNCLASSIFIED

In the way indicated, we arrive at an energy-loss cross section which is not more than 3.5 barns. This corresponds to a mean free path in air of about 57 meters. Only a sphere of 57 meters radius can retain a substantial part of the energy produced. At least such a volume must be heated in order that the thermonuclear reaction be sustained.

An air sphere of 57 meters radius contains about $4(10)^{31}$ nuclei, and $3(10)^{32}$ electrons. For it to be heated to a nuclear temperature $T_n = 10$ Mev ($T_e = 0.4$ Mev) requires about $7.5(10)^{32}$ Mev of energy.

A fission bomb produces about $5(10)^{26}$ Mev per kg of active material, when working with 100% efficiency. If also all the produced energy goes to produce the air temperature, then $1.5(10)^{6}$ Kg of material would have to be burned up in order to obtain the dangerous 10 Mev temperature. Actually at most 1 % of the bomb energy may be available to produce the temperature; the rest goes into useless radiation.

A super-bomb, burning deuterium, may be more dangerous than a fission bomb because its energy is not put into radiation as it is within the fission bomb. The deuterium nuclei have too small charge to cause efficient radiation. In the burning of a deuterium nucleus at most about 6.4 Mev can be produced, and that only if every secondary triton and He^3 nucleus also reacts. Thus about 2.5 times as many deuterons must be burned as there are air nuclei to be heated to the 10 Mev temperature. To heat the 57-meter sphere of air, at least an 8-meter-radius sphere of liquid deuterium must be burned.

The assumption made here thus far, that the N + N reaction energy is mainly released in the form of alpha particle kinetic energy, may in one respect lead to an underestimate of the danger. If, as mentioned in the footnote on page 4, the reaction $N + N \longrightarrow O + C + 10.6$ Mev is the most frequent of the N + N reactions, then the situation is made more dangerous by the short ranges of the O and C nuclei. An estimate similar to the one made for the

 [redacted]

alpha particles shows that the energy will be deposited within a radius of only 7 meters instead of being spread over a 57-meter-radius sphere, as is the alpha-particle energy. To heat a 7-meter-radius sphere of air to the dangerous 10-Mev nuclear temperature requires the energy released in the fission of about 3 tons of active material. If a super-bomb is used, a sphere of liquid deuterium only 1 to 1.5 meters in radius may suffice.

The apparently dangerous situation discussed in the preceding paragraph has one redeeming feature, as compared to the case in which N + N reactions produce mainly alpha particles. The total energy evolved is only 0.6 as great. This means that the minimum safety factor 1.6 which applies to an energy release of 17.7 Mev per reaction, is now increased to 1.6/0.6 = 2.67. There is therefore so much less chance that the estimates here are in sufficient error to affect our conclusions.

Several further effects exist which may make less of the energy released by bombs available for carrying on a reaction in the air. There may be various hindrances to the transfer of the energy from the bomb to the air nuclei. There also can be expected various hydrodynamic effects; a limited heated volume will expand against cold surroundings and thus lose energy to them, making reactions within itself more difficult. However, all these additional avenues of energy loss are difficult to calculate with certainty; if one goes on with the policy of making the most dangerous assumption wherever any uncertainty exists, then the effects in question must be left out of consideration for the time being.

5. INVERSE COMPTON EFFECT

There is one further effect which increases radiation losses: the inverse Compton effect. We can present here only crude estimates on the quantitative consequences of this effect. But even a qualitative discussion

[redacted]

shows that the inverse Compton effect acts to quench nuclear disintegration of the atmosphere as soon as this reaction has extended over a radius of a few hundred meters.

If a relatively small air mass is heated, the radiation emitted will simply escape. But if a greater sphere of air is heated, the quanta of electromagnetic radiation are likely to make Compton collisions with the electrons before leaving the sphere of hot air. In such collisions the quanta will, on the average, gain energy from the hot electrons. The end effect is that more energy is going into radiation and more energy will become unavailable to the thermonuclear reaction. It can be shown* that the ratio of the Compton losses to the bremsstrahlung losses for an electron at temperature T_e in air is

$$(10/3) \quad (T_e/mc^2) \quad R/\lambda$$

if the electron is subjected to the radiation of the air electrons at temperature T_e contained within a radius R. λ is the Compton mean free path in air, amounting to 42 meters.

The dangerous electron temperature is 400 Kev, making $T_e/mc^2 \approx 0.8$. At this temperature the above, unrelativistic, formula for the Compton loss is not strictly valid. We may use it nevertheless as a crude estimate since the electron gas is not strongly relativistic.

In a heated sphere of 57-meter radius (discussed in the previous section) the losses due to radiation are multiplied by 4.6 through the Compton effect. This makes the safety factor 4.6 x 1.6 = 7.4 against detonating air if the alpha-producing N + N reactors are relied upon. In a heated sphere of only 7 meters radius the radiation losses are increased only about 40% by

UNCLASSIFIED

* See LA-401

[redacted]

the Compton effect. Thus, if N + N → C + [illegible] reactions predominate, the safety is increased only to 1.4 x 2.67 = 3.8.

In spite of the considerable magnitude of these safety factors it is not inconceivable that our estimates are greatly in error and thermonuclear reaction may actually start to propagate. In that event the Compton effect will quench the reaction as soon as a sufficiently great air mass is affected by the reaction.

It is clear that the quenching becomes serious as soon as the reacting region becomes greater than a sphere of ~50 meter radius. The reaction, however, may still proceed in a spherical shell with a thickness smaller than 50 meters. After some time this shell can be treated as a plane detonation wave.

According to the Chapman-Jouguet relations the velocity of this detonation wave is $\left[(\gamma + 1)/\gamma\right] C_S$ where γ is the ratio of the specific heats; i.e., $\gamma = 5/3$ for a completely ionized gas and C_S is the sound velocity in the hot gases behind the detonation front. Assuming kT = 10 Mev for these hot gases the Chapman-Jouguet velocity will be 5×10^9 cm/sec. It is not clear that the Chapman-Jouguet relation is applicable in the present case. But if we apply it we obtain the minimum velocity of propagation consistant with the conservation laws for a uniformly moving plane disturbance.

Thus the detonation velocity is greater than 5×10^9 cm/sec or C/6. Even if light escapes from such a reaction zone the detonation front will catch up with the radiation, which spreads by diffusion and therefore propagates with a decreasing velocity. In fact radiation needs a time $t = (3/2)\ N^2\ (\lambda/C)$ in order that the mean square diffusion distance from the plane of origin should become N^2 times the square of the mean free path λ. For the diffusion velocity we may write $dN/dt = C/3N$. Setting this velocity equal to the minimum velocity with which the detonation wave propagates, one obtains $C/3N = C/6$ or $N = 2$.

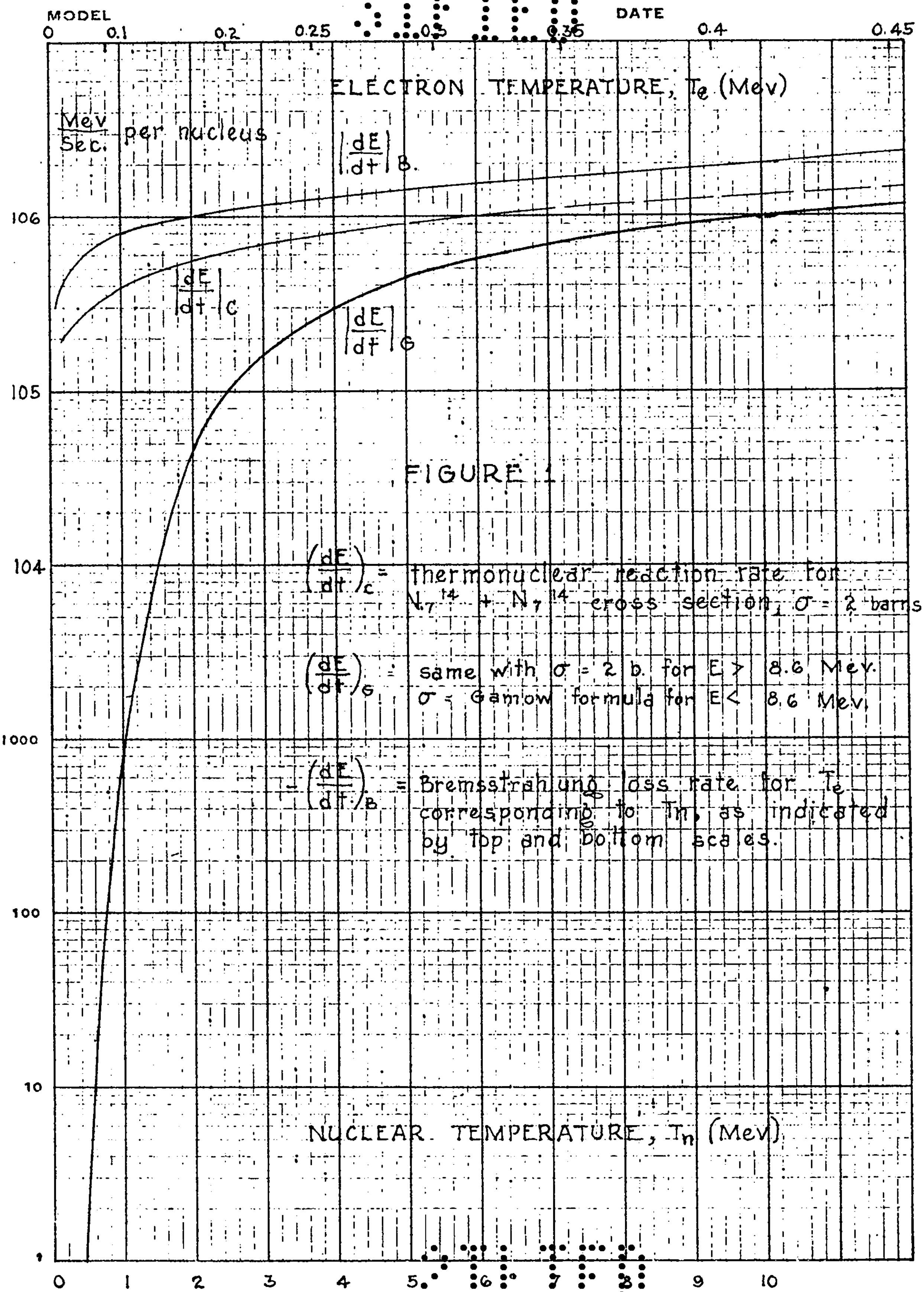
[redacted]

With $\lambda = 42$ meters one sees that the quenching by Compton effect must become important as soon as the detonation wave has travelled ~ 100 meters. Since this length is quite small compared to the depth of the atmosphere, there is no danger that radiation can escape from the atmosphere as a whole and thus become unusable in the Compton effect.

While the above numbers may be somewhat in error, the quenching must eventually take place as long as the detonation wave is a simple plane perturbation. There remains the distant probability that some other less simple mode of burning may maintain itself in the atmosphere.

Even if the reaction is stopped within a sphere of a few hundred meters radius, the resultant earth-shock and the radioactive contamination of the atmosphere might become catastrophic on a world-wide scale.

One may conclude that the arguments of this paper make it unreasonable to expect that the N + N reaction could propagate. An unlimited propagation is even less likely. However, the complexity of the argument and the absence of satisfactory experimental foundations makes further work on the subject highly desirable.


MODEL
DATE
0 0.1 0.2 0.25 0.3 0.35 0.4 0.45
ELECTRON TEMPERATURE, Te (Mev)
Mev/Sec. per nucleus
|dE/dt|B
|dE/dt|C
|dE/dt|G
106
105
104
1000
100
10
1
FIGURE 1
(dE/dt)c = thermonuclear reaction rate for N7 14 + N7 14 cross section, σ = 2 barns
(dE/dt)G = same with σ = 2 b. for E > 8.6 Mev. σ = Gamow formula for E < 8.6 Mev.
- (dE/dt)B = Bremsstrahlung loss rate for Te corresponding to Tn, as indicated by top and bottom scales.
NUCLEAR TEMPERATURE, Tn (Mev)
0 1 2 3 4 5 6 7 8 9 10
KEUFFEL & ESSER CO., N. Y. NO. 359-
MADE IN U.S.A.

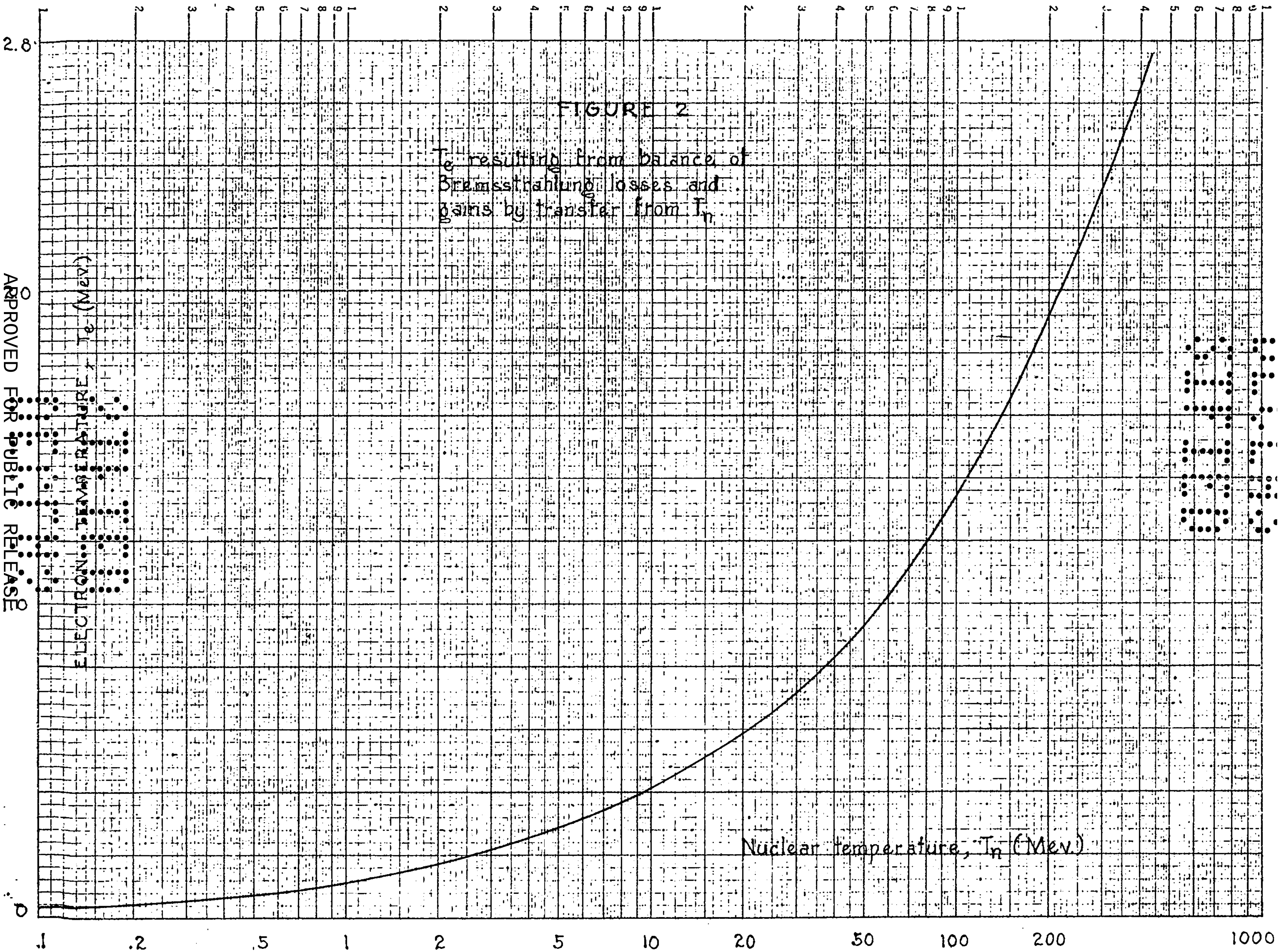
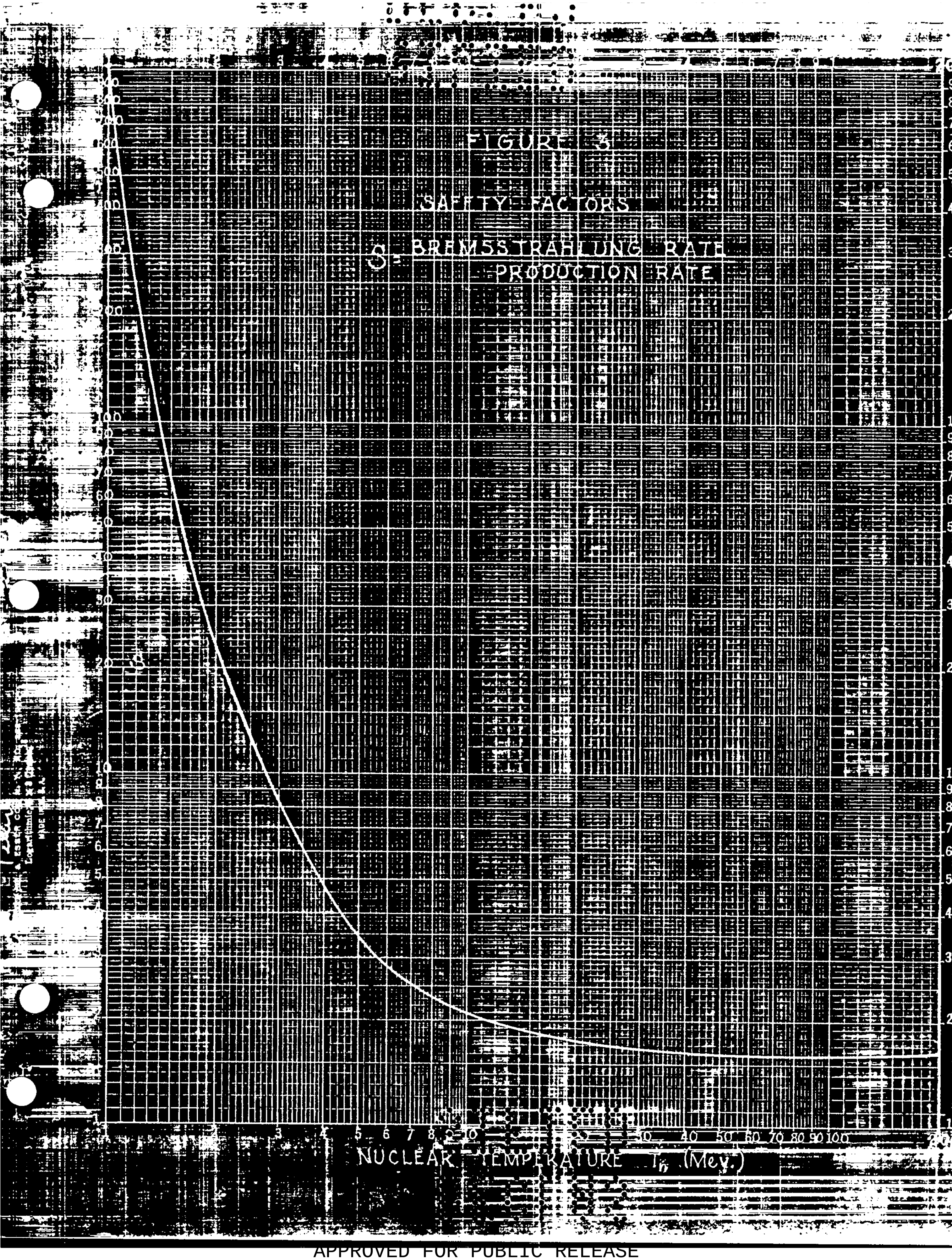


FIGURE 2

T_e resulting from balance of Bremsstrahlung losses and gains by transfer from T_n

APPROVED FOR PUBLIC RELEASE



APPROVED FOR PUBLIC RELEASE

UNCLASSIFIED

DOCUMENT ROOM

REC. FROM gc

DATE 8/23/46

REC. ...... NO. REC. ✓

UNCLASSIFIED

APPROVED FOR PUBLIC RELEASE