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# SOME REMARKS ON IRAQ'S POSSIBLE NUCLEAR WEAPON CAPABILITY IN THE LIGHT OF SOME OF THE KNOWN FACTS CONCERNING NUCLEAR WEAPONS

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## SUMMARY

Before the Gulf War it was known that Iraq had a modest amount of weapon-usable, highly enriched uranium. in the form of fuel elements for two research reactors. This material could have been dispersed or buried beneath rubble as a consequence of the bombing of their nuclear facilities, or it could have been moved to safe storage before the bombing; but nothing is publicly known about that. Iraq could hold additional amounts of weapon-usable material, obtained clandestinely, and undisclosed; but nothing is known about that, either.

To avoid embarking on an unduly speculative discussion the question addressed here is that of what could be done to manufacture one or more nuclear weapons with the material the Iraqis were known to have had available. prior to the war. Since nothing is known -- at least, nothing is known to the author -- about the capabilities of indigenous Iraq technology in the various specialities required, the important question of whether the Iraqis were or are currently in a position to carry through without aid all the steps necessary to realize "what could be done" is necessarily left aside. In view of their devious efforts -- recently unmasked -- to import items of possible use in contravention of existing export controls, there has been some considerable speculation on this point. It can be stated generally, however, that for a new project to have a device in hand, a fairly large and competent staff, with diverse experience and capabilities, would have to work intensively for at least a year on design, fabrication and assembly of the device.

As to "what could be done" by such a group the following discussion suggests that with only 12.3 kg of highly enriched uranium on hand (this being one of the two batches known to have been available to Iraq.) no damaging nuclear explosion would be possible using the (simpler) gun-type assembly method. With a commendably effective use of the implosion method it should be possible to realize a yield of the order of 10 kilotons in a device in which the nuclear components and HE weighed only a ton, or so, provided beryllium metal technology were available., or weighing

several times more if the use of beryllium as a reflector were not feasible. With 22.3 kg of enriched uranium (the combined total of the two batches held by Iraq) an explosion of the order of a kiloton might just be managed. from a gun-type assembly with free use of beryllium; but not otherwise. By effective use of the implosion approach (and without beryllium) it should be possible to realize a yield of the general order of 20 kilotons in a total weight of a ton, or so. -- excepting components, such as protective packaging and electrical items, outside the HE. By dividing the total uranium supply into two units, and using implosion, it would seem marginally possible to produce two explosions having yields of the order of 100 tons.

With the possible exception of this last option there would not be enough material to allow for a proof test of the model to be used as a weapon. There are, of course, modes and aspects of what is frequently referred to as "sophistication" by which more favorable performance might be realized. However, inasmuch as a full yield proof test (or tests) would be necessary before there could be any assurance that a proper exercise of such approaches were in hand, such possibilities fall outside the range of the present discussion.

# Some Remarks on Iraq's Possible Nuclear Weapon Capability in the light of Some of the Known Facts Concerning Nuclear weapons



## I. Introduction.

There has been a great deal said about the nuclear weapon capability of Iraq: "a decade away", "within a year", "sooner than many people think", etc. etc. mostly by press correspondents referring to unspecified "intelligence sources." It is *not* proposed to comment here on these divergent reports or their various motivations.It *is* proposed to set down some of the elementary considerations which the Iraqis -- or anyone else -- will have to take into account in planning to build a nuclear explosive device. These have all been described many times, in many places; but they have not been much referred to in the recent flurry of speculation.

## II. Things Known

### a) The Notion of Criticality

An assemblage containing fissile material is said to be "critical" if one fission occurring in the system results on the average in one subsequent fission. Of the two, or three, or so, neutrons released in the initial fission only one (on the average) causes a subsequent fission, the others being absorbed or captured in non-fissioning material that may be present or escaping from the boundary of the system In such an assembly a chain reaction will be maintained at a constant rate with a constant population of neutrons, as is the case in a power reactor running at constant power.

In an assembly similar in all respects to a critical system except for being somewhat smaller, the likelihood that a neutron will escape will be somewhat larger and the likelihood that a neutron will

cause a subsequent fission will be somewhat reduced so that an initial fission will, on the average, result in less than one subsequent fission. A chain reaction will then proceed at a diminishing rate and the neutron population will ultimately -- and perhaps rapidly -- fall to zero. Such an assembly is referred to as "subcritical."

In an assembly similar to a critical system except for being somewhat larger the likelihood that a neutron will escape will be smaller and that it will cause a fission will be somewhat increased. so that an initial fission will result on the average in more than one subsequent fission. The chain reaction will proceed at an increasing rate and the neutron population will rise; and this will continue indefinitely until the energy from the fissions occurring should disrupt the assembly and render it subcritical. Such an assembly is referred to as "supercritical"; and the degree of supercriticality can be indicated by the ratio of the mass of fissile material in the larger system to the mass in the critical system -- often referred to as the "number of crits."

b) Some Critical Masses

Whether any particular system is critical or not depends fundamentally on the characteristics of the fissile material involved (whether U-235 or Pu-239) but there is no unique value for the mass of that fissile material required to establish criticality. Great variations in the critical mass can result from such features as: whether or not the part of the assembly containing the fissile material (referred to as the "core") is surrounded by a neutron reflector and, if it is, by the thickness and neutron characteristics of the material in the reflector; whether the fissile material is in a pure form or is diluted by inactive atoms -- as in the oxide ($UO_2$) or in uranium of low enrichment; whether the fissile material is in the form of metal or in a solution; and other factors.

Such effects are listed in the following Table. The enrichment of the uranium in the fissile core is between 93 and 93.5% in all cases

except for the second and third items for which the enrichments are 80 and 50% respectively. Except for the final item for uranium oxide all the cores are uranium metal at normal density. The numbers listed are as read from the experimentally-based curves given in the Los Alamos report LA-10860-MS (1986 Revision), and may differ in detail from the values listed in other tabulations of similar quantities. However, any such differences are unlikely to be of any importance for the present discussion.

Table

Selected Critical Masses of Highly Enriched Uranium

| Core | Reflector (thickness, cm) | Critical Mass (kg U) | Core Radius (cm) | Assembly Mass (kg) |
|---|---|---|---|---|
| U(.935) | None | 52.5 | 8.75 | --- |
| U(.8) | None | 66 | 9.45 | --- |
| U(.5) | None | 155 | 12.5 | --- |
| U | Be(2) | 33 | 7.5 | 37 |
| U | Be(5.5) | 21.5 | 6.5 | 33 |
| U | Be(9) | 16 | 5.9 | 40 |
| U | Be(15) | 12 | 5.3 | 75 |
| U | Be(20) | 10.6 | 5.1 | 130 |
| U | U(Nat)(6.8) | 21.5 | 6.5 | 240 |
| U | U(Nat)(20) | 17 | 6.0 | 1360 |
| U | $H_2O$(10) | 24.5 | 6.8 | 43 |
| $UO_2$ ($\rho$(U)~9.5) | $H_2O$(10) | 42 | 10.2 | 78 |

From the Table it may be seen that by the use of progressively thicker beryllium metal reflectors the critical mass can be reduced by a factor of about five below the critical mass without a reflector -- though the last few kilograms gained entail increasing cost in overall size and weight. Any material may be used as a reflector and

will result in critical masses smaller than the bare critical mass Most such materials will be very much easier to acquire than beryllium metal; but their effects on the critical mass will be much less extensive. For example, iron or water could be used. to cut the bare critical mass by a factor of about two; and with natural uranium one could achieve a factor of three, though that would require over a ton of uranium.

It may also be seen from the Table that a kilogram of uranium of 80% enrichment is "worth" only about eight tenths as much (52.5/66) as a kilogram of 93% enrichment. Such "worth ratios" are fairly stable and would apply in good approximation to a wide range of core-reflector combinations. For example, a ratio quite close to one-to-three between the critical masses of $\delta$-phase Pu-249 ($\rho$ = 15.7 g/cc) and 93% enriched uranium in the same reflector material and thickness holds all the way from a bare assembly down to reflectors for which the critical mass of 93% uranium is under 20 kg. As an additional comment on this point it appears from the Table that uranium oxide at its highest available density (crystal density of $UO_2$ ~ 11g/cc) is worth only about 60% as much as uranium metal.

c) Hydrides

The observations made so far concerning critical masses have been restricted to what are termed "unmoderated cores" -- that is, core materials in which no specific feature is included to reduce the energy of the neutrons, or "slow them down." On the average, when a neutron collides with a hydrogen nucleus its energy after the collision is about a third (more precisely, $1/e$) of its energy before colliding. The fission cross-section of U-235 is very much larger for slow neutrons than for fast (fission) neutrons. Consequently, by including hydrogen along with the U-235 in a fissile core one can open up a new (and lower) range of critical masses than are available with unmoderated cores. Hydrogen could be included by using the solid compound $UH_3$, or by forming a solution containing one or another concentration of some soluble uranium compound, or by preparing a

compact of finely divided uranium and some hydrogenous substance such as paraffin. With the major exception of the solid $UH_3$ the neutronic characteristics of materials of the types suggested can be reasonably approximated by those of an ideal homogeneous mixture of uranium metal and water having the same hydrogen to uranium atomic ratio. From the Los Alamos report already referred to, the critical masses of 93% enriched uranium in a few metal-water mixtures with $H_2O$ reflectors are the following: for $UH_3$, 21.4 kg; for $UH_5$, 17.9; for $UH_{10}$, 12.4; for $UH_{30}$, 5.2; for $UH_{100}$, 1.9; for $UH_{500}$, 1.0. Adding hydrogen atoms beyond 500 to 1 results in larger critical masses. If, instead of a mixture of uranium metal and water, one should consider a mixture of $UH_3$ and water, one could achieve the same moderation effect with one and a half fewer water molecules per uranium which would reduce the negative effects of dilution with inert material and result in smaller critical masses in the first few entries. And, indeed, from the results of a recent experiment it appears that the critical mass of $UH_3$ (without water in the core) is close to 17 kg rather than the 21.4 listed above. Though the reductions in the critical masses of $UH_5$ and $UH_{10}$ are likely to be smaller, one may suppose that critical masses smaller by a kilogram or so could also be realized for those hydrides.

The purpose of this discussion of hydrides has been to bring to attention that there is a class of materials with critical masses at, or below, the low end of the range connected with assemblies having unmoderated cores. Of the materials listed, those with the largest hydrogen ratios do not have a meaningful explosive potential; but at least several of those with the leaner hydrogen ratios could be used to produce explosions though these would no doubt be on a much smaller scale than the familiar examples of Hiroshima and Nagasaki. As reported in the unclassified "Project Y: The Los Alamos Story" considerable attention was given to the study of hydrides starting from the earliest days of the wartime project. This was because it was recognized from the start that a hydride system would have a smaller critical mass than a pure metal system and this was at a time before it was known how much enriched material would actually

be needed to make a critical metal assembly or how long it would take the enrichment plants to produce that much material. As the work progressed the prospects on the two latter points became more favorable and more assured. It also soon became clear that, if it could be built, a metal system would out-perform a hydride system After about a year's work it became fairly certain that a metal system could be built -- i.e. there would be enough material -- and further war-time work on a hydride weapon was abandoned. This did not mean, however, that it was concluded that a hydride could not be used to produce an explosion.

d) Effects of Compression

Quite apart from the effects on critical masses which may be realized by the use of reflectors or of hydrides with materials at normal density there is the extremely important point of the effect of changes in density (such as an implosion could induce) on the critical mass in assemblies of any type.

Let us suppose we have a critical system in which the core mass is $M_o$ , the core radius $r_o$ (cm), the density of material in the core is $\rho_o$ (gm/cc), and that the distance a neutron travels on the average from the time it is born till it collides with a nucleus in the material in the system is $\ell_o$(cm). If we have a quantity of the same material (core and reflector) at a different density (x times the previous density in both core and reflector) then the new core density will equal $x\rho_o$ and the new path length $\ell$ will equal $\ell_o/x$. A mass M at this new density with radius r will be critical if $r/\ell = r_o/\ell_o$ since the probability of a neutron escaping, or causing a fission. etc., will be the same in the two cases. From this criticality condition we have $r = r_o/x$; and the critical mass $M = 4\pi/3\ \rho r^3 = 4\pi/3 \cdot (x\rho_o)(r_o/x)^3 = 4\pi/3\ (1/x^2)\rho_o r_o^3 = (1/x^2) M_o$.

From this relationship between critical masses at various densities it will be seen that if a critical mass at normal density should be compressed by a factor of two in density it will become highly

supercritical and constitute four critical masses at the new density. Similarly, if an amount of material constituting half a critical mass at normal density should be compressed by a factor of two it would also become quite supercritical and constitute two critical masses at the new density. Similarly, again, if we suppose we have a core-reflector system in which the critical mass is 25 kg of uranium at normal density (18.8), and suppose, further, that we assemble (as by the gun assembly method) 50 kg of that combination at normal density, we would then have a supercritical assembly consitituting two critical masses and having a core radius of 8.6 cm. If we now suppose that this assembly starts to blow apart in such a way that the density of both the core and reflector decrease uniformly by the same factor, then, by the time the original core density of 18.8 shall have fallen to $18.8/\sqrt{2}$ (=13.3), which will occur when the core radius has grown to 9.65 cm, the system will be just critical. As the expansion proceeds beyond that the system will be subcritical and the neutron chain reaction will shortly come to an end. (Of course, the assumption of a uniform expansion in the core and reflector materials does not correspond to what would actually happen; but, nevertheless, the picture is qualitatively correct in showing that it requires only an apparently small amount of displacement of material -- as from 8.6 to 9.65 cm -- to abate the supercriticality of such a system.

e) Efficiency

By efficiency is meant the ratio between the energy actually realized in some particular instance and the total energy which would result from consuming all the fissile material present. In contrast with the situation applying to critical masses, for which an enormous amount of specific and official information has been published, there is very little specific information publicly available concerning efficiencies. However, even that little provides some qualitative orientation.

One may first note that if one kilogram of uranium (or plutonium) undergoes fission the energy released amounts to about 17.5 kilotons (KT) of high explosive (HE) equivalent -- where, by definition, HE is said to release one kilocalorie per gram, and the ton is the metric ton of one thousand kilograms. The yield of the weapon exploded at Nagasaki was about 20 KT; so a little more than one kilogram of material was burned. The weapon has been described as a solid assembly containing nearly a critical mass of $\delta$-phase plutonium in a thick uranium reflector (or tamper). The critical mass of plutonium under such conditions is around 7 kg, so there must have been something like 6 or 7 kg Pu in the core. Having consumed 1.14 kg, the efficiency appears to have been in the range of 16 to 20%. Or, stated differently, the yield was roughly 3 KT per kilogram of fissile material in the core.

The fissile material in the weapon used at Hiroshima was enriched uranium Being a gun-assembled device, the material was at normal density. The yield was about 15 KT, so that about 0.85 kg was fissioned. We do not really know just how much enriched uranium was present; but in The Curve of Binding Energy by John McPhee it is stated (p. 14) that some 60 kg were in the bomb. That this may be a fairly good number -- good enough, in any case , for our needs here -- is supported by the information given in The Los Alamos Story that the total amount of U-235 received at Los Alamos by the time fabrication of the device would have to have started was about 50 kg. This 50 kg of U-235 was in uranium of which the enrichment improved over the year during which it was delivered from 63% to 89%. To assume a core mass of 60 kg containing about 50 kg of U-235, and hence having an average enrichment of about 80%, is, at least, consistent with the information given above. On this basis the efficiency (with 0.85 kg burned) would have been about 1.4%; and the specific yield (with 15 KT from 60 kg) was about 250 tons per kilogram of material in the core.

For a rough estimate of the degree of supercriticality of the Hiroshima device we first recall our earlier observation that on a criticality scale 60 kg of 80% material would be equivalent to about

50 kg of 93% material. This may be viewed in the context of the critical mass data already presented. Beryllium metal was not considered at that time as a reflector for a weapon core, partly because it wasn't available in the large-sized pieces required, and partly because it was felt that a much more dense material would do better at holding back the expansion of the exploding core. Uranium, which was very favorable with respect to density and neutron reflecting properties, was deemed unsuitable for use as a tamper in a gun-assembled system. Great efforts were directed to achieving as rapid an assembly as could be realized by the gun method, and to producing uranium of unexampled purity so that its neutron source should be as small as possible. The motive for this was to reduce the probability of predetonation to the lowest feasible level. Predetonation refers to the situation in which a random neutron brings on a nuclear explosion before the assembly is complete and while the yield is lower (possibly very much lower) than the intended yield. The probability of predetonation is proportional to the product of the assembly time and the neutron source strength. In view of these considerations it was out of the question to use as a reflector a material like uranium which, because of its spontaneous fission rate, would introduce a neutron source more than ten times larger than that inherent in the core itself. Some other material which produces no neeutrons would be called for, even should its density and neutron reflecting characteristics be less favorable than those of uranium. We shall assume that the Hiroshima device used some reflector material at some moderate thickness (since the thicker the reflector the larger the weight of other weapon components would have to be) for which the critical mass of 93.5% uranium would have been about 25 kilograms and, hence, the critical mass of 80% material about 30 kilograms. On this basis it will be supposed that when assembled the core of the Hiroshima device constituted about two critical masses. [Incidentally, it should be noted that for an implosion system the assembly time is more than an order of magnitude shorter than for a gun assembly, so that the undesirable aspects of uranium as a reflector in connection with a gun assembly are reduced to the point of no longer being significant.]

f) Factors Affecting Efficiency

To achieve an explosion it is obviously necessary to start with a supercritical assembly. In a system employing materials at normal density this can only be done by increasing the amount of material. In an implosion system it can be done by increasing the density In either case the more supercritical the starting assembly, or the larger the number of critical masses achieved, the higher the efficiency of the resulting explosion. In the "Los Alamos Primer", which was a report of a series of lectures prepared by Robert Serber and delivered at the very beginning of the war-time Los Alamos project, Serber presented a rough and approximate formula -- which would be valid only for small or moderate degrees of supercriticality -- for the efficiency of a nuclear explosion . The efficiency was expressed as the product of several factors, some of which depended primarily on the nuclear properties of the fissile material employed (and would, consequently, have different values for plutonium than for enriched uranium) but one of which indicated the dependence on the degree of supercriticality -- at least in a qualitative way. On lumping the other terms together as a proportionality factor K, Serber's formula for the efficiency $\phi$ can be written in the form $\phi = K(r/r_0 - 1)^3$, where r is the radius of the actual supercritical assembly and $r_0$ is the radius of the critical mass at the density involved. Since $(r/r_0)^3$ equals N, the number of critical masses in the starting system, this may also be written as $\phi = K \cdot (\sqrt[3]{N} - 1)^3$. This quantity, which is equal to zero when N = 1 -- as it most certainly should -- remains quite small for values of N only a little larger than one. For instance, if one considers the value of $\phi$ for the sequence of values N =. 1.25, 1.5, 1.75 and 2, it will be seen that the first three of these are smaller than the efficiency for N = 2 by factors of approximately 40. 6, and 2, respectively. In general, it requires a considerable degree of supercriticality to get much of an efficiency.

One may also consider the efficiency in a somewhat different way. Obviously by the time the chain reaction has developed an energy density (and, consequently, a pressure) in the material of the core which is equal to one, or a few, times that realized in detonating HE, the core material will start to blow apart and throw off whatever may be surrounding it -- much as HE does. In view of the fact indicated above that a rather small distance of displacement suffices to convert a fairly supercritical assembly to a subcritical state the time required will be short -- at least by ordinary standards. Yet this sort of time interval -- or, actually, a much shorter one since the pressure is continuing to rise to much higher levels than that provided by HE -- is the only time available for the chain reaction to amplify the energy level from that associated with HE to the greatly higher levels associated with nuclear explosions. In the case of the Nagasaki weapon in which, as already mentioned, the energy developed was about 3 KT per kilogram, the amplification factor was something like $3 \times 10^6$, while for the Hiroshima weapon it was less than $3 \times 10^5$. These quite enormous numbers, and their difference, call attention to the decisive influence of the rate at which the level of the chain reaction is increasing. The factors which govern this are embedded in the quantity K in Serber's efficiency formula. A term of central importance in this connection is the average neutron lifetime -- that interval between the moment a neutron is born and the moment it causes a subsequent fission. The shorter that lifetime the more rapidly the level of the chain reaction will increase. The lifetime will be shorter in material with a larger fission cross-section since the neutron doesn't have to travel so far. And for the same reason it will be shorter in material at higher density where the atoms are closer together. Similarly, the greater the neutron velocity the shorter the lifetime, except that this consideration no longer applies in a straightforward manner in those regions of the neutron energy spectrum where the fission cross-section changes markedly with the neutron velocity. In the Nagasaki device the fissile fuel was plutonium which is more favorable than enriched uranium in the respects mentioned, and in addition it was in a compressed state. Thus the rate of increase in the reaction level will have been larger

than at Hiroshima, and that will have accounted for some part of the ten-fold increase in the amplification factor. It is also possible, of course, that that device was considerably more supercritical than the (roughly) two-crit type of device seen at Hiroshima.

The fact that favorably low critical masses may be available in systems using hydride cores has already been mentioned. This comes about because of the very large fission cross-section in U-235 for neutrons at very low energy. To take advantage of this the fast neutrons emerging from fission have to collide with hydrogen a number of times to reduce their energy. The time required for the necessary successive collisions must be included in the neutron lifetime. The condition of criticality is totally indifferent to this lifetime; but the progress of an explosion is not. As a result, though the leaner hydrogen-uranium mixtures considered earlier are surely capable of producing explosions of some size the more thorough the moderation required to establish the criticality feature the longer the neutron lifetime and the smaller the rate of rise in the chain reaction level and the smaller the amplification factor that can be realized. It would be difficult to develop a confident quantitative estimate; but one might expect that by or before one should follow this line as far out as $UH_{30}$, available yields would have fallen into the range of one or a few tons per kilogram.

At the extreme end of the series considered -- $UH_{500}$, where the critical mass was the smallest that could be reached by moderation with hydrogen -- one is in the general region applicable to light water power reactors. It has often been said that such systems are totally incapable of producing a nuclear explosion. That is correct, and for the sort of reasons just outlined in connection with possible hydride explosions. While an increasing chain reaction might somehow get established in such a machine the neutron lifetime is so long that the rate of increase is quite small (at least on the sort of time scales applicable in the kind of systems we have been considering). Well before the energy levels in the fuel reach that provided by HE the pressures in the fuel rods and moderator will have

disrupted the internal geometry or expelled material from the system and cancelled out the supercriticality so rapidly that the nuclear energy released by the slowly rising chain reaction will not have managed to amplify greatly before the reaction is cut off. Even the dramatic event of Chernobyl does not provide a counter-example to this. After the affair was over the energy which had been developed in the fuel was reported as being 1.5 kg HE equivalent per kilogram of fuel, and over the interval in which the energy accumulation was rising most rapidly it required about half a second to develop half of this. The famous explosion which lifted the roof and caused so much externally evident damage was driven by pent-up steam. It was not a "nuclear explosion" in the sense we have been considering.

Of course, there is an endless list of other "things known." The only additional one to be mentioned here is the fact that the Iraqis have a limited amount of enriched uranium on hand. Discussion of what could be done with this is the subject of the following section.

## III. Possibilities.

### a) Iraq's Uranium Holdings.

Iraq is known to have two batches of enriched uranium available -- at least this was the case prior to the Gulf War. It is possible that one, or both, of these were lost to them as a result of the bombing of their nuclear facilities; but nothing is known about that, and it is at least equally possible that these batches were recoverable or were removed to safety before the bombing. It is conceivable that they acquired additional supplies of fissile material clandestinely; but there is no definite evidence of that beyond the indication that they would have done so if they could. Similarly, much has been made of the possibility that Iraq might sometime be able to produce material suitable for use in weapons -- either highly enriched uranium or plutonium. However, such reactors as they are known to have operating (and this is one of the few points on which intelligence sources ought to have reliable information) are in-

capable of producing plutonium at a rate which would result in a significant accumulation in less than some number of years. With respect to their efforts to acquire ultra centrifuges for enriching uranium (and they do appear to have directed serious attention to this) available evidence is to the effect that they are still some years from having an operating facility capable of producing enriched uranium. Even after such a facility should be operating it would require some time -- years or months, depending on the size of the plant -- before its output could have an important effect on the total supply of weapons-usable material. It has also been said that the Iraqi are engaged in efforts to obtain supplies of uranium by mining; but any such activity precedes the effective use of an enichment facility by an extended period. Consequently, the balance of this discussion will be limited to that of the sort of things which might be achieved by an organization -- Iraqi, or other -- which had access to such amounts of material as Iraq is presently said to have.

The two batches were: 12.3 kg of 93% enriched metal in the form of fuel elements, which were probably irradiated to a modest extent over ten years ago but from which the uranium could now be separated in a rather short time; and 10 kg of 80% enriched uranium oxide, some part of which may have been irradiated recently -- though to an unknown extent. Irradiated fuel could be difficult to handle, depending on the level of irradiation, and the time since it occurred, the capability available for separating out the radioactive contamination and the criteria set for acceptability of radiation exposures. Little, or nothing, is known about these aspects of the situation..

b) Processing

Various effective procedures for converting $UO_2$ to metal have been described in published reports; and from what has already been noted in I b) concerning the relatively low "worth" of $UO_2$ (on a criticality scale) it will be assumed that this conversion is made. [It is also assumed that the 10 kg ascribed to this batch refers to the

mass of uranium in the material. If it refers to the mass of the oxide there would be only 8800 gm of uranium.] The total uranium reserve is, then, 22.3 kg of metal consisting of two separate units: 12.3 kg at 93% and 10 kg at 80%. With the factor of 0.8 for 80% material, the reserve is about 20.3 kg of 93% equivalent. Blending these two units would provide 22.3 kg of 87% material. The worth factor for 87% is close to 0.9, so this new unit would be about 20 kg of 93% equivalent -- slightly smaller than the sum of the worths of the separate units. Nevertheless, this blended form might well be favored, since in fabrication it could conceivably require only one finished part whereas in the two-unit form at least two finished (and fitted) parts would be needed.

In fabricating metal parts -- as with casting followed by machining -- it is necessary to start with somewhat more material than will be present in the finished part; and the more demanding the specifications as to dimensionality and smoothness, or the more complicated the shape -- as in a shell in which two surfaces have to be finished, rather than a solid shape -- the larger this overage will need to be. Something of the order of 10% -- though not much smaller -- can be realized with good practices and experience in the case of simple shapes. Of course, the scrap resulting from the trimming and smoothing required to obtain a finished piece can be returned to inventory for use in subsequent fabrication -- but not to a first and only piece. At least with respect to metal systems, such unavoidable losses imply that the masses actually present in finished product will be smaller than the total reserve by a kilogram or two.

c) Possible Cases.

Two particular examples will be considered.: A. uranium reserve of 12.3 kg of 93% material -- as might apply in the event the 80% batch were not available either as a result of bomb damage or inability to handle the irradiated material; and, B, uranium reserve of 22.3 kg (blended) of 87% material, but equivalent to only 20 kg at 93% enrichment.

* Case A. From the data presented in I b) a supercritical assembly might just be possible from 12.3 kg in metal at normal density. This would require the use of quite thick beryllium, and even at that the degree of supercriticality would be very small. There are hazards in handling beryllium; and the metal is expensive and difficult to work. Not every industrial base is prepared to produce it. With the low level of supercriticality which could be realized the considerations outlined in I f) suggest that the efficiency would be smaller than that in a two-crit system by a factor of more than one hundred -- which is to say that the energy release might be something in the range of a ton per kilogram, or less.

With respect to an assembly using a hydride at normal density it may be seen from I c) that 12 kg of uranium is not enough to enable one to do anything with $UH_3$ or $UH_5$. It might be enough to achieve a supercritical assembly with $UH_{10}$; but, if it is, the degree of supercriticality would be so small that. as discussed above, the efficiency would be too low to be of interest. However, 12 kg would be enough to provide for a two-crit assembly of $UH_{30}$, so one needs to ask what sort of explosion that would produce. The first thing to notice is that the density of uranium in $UH_{30}$ is less than 1 gm/cc; that is, about 20 times smaller than in uranium metal. Thus, the lifetime of neutrons traveling with the same velocity, and having the same fission cross section that applies in metal will be 20 times larger. However, the velocity is reduced by moderation (which would further increase the lifetime) while the fission cross section is larger for the slower neutrons (which works in the opposite direction). For a fully moderated neutron (energy about 0.025 electron volts) the velocity is smaller than that of a typical neutron in a metal system (energy in the neighborhood of one million electron volts) by a factor of about five thousand, while the fission cross section is larger by a factor of only about five hundred. For such neutrons, therefore, the moderation effect is to increase the lifetime by a factor of about ten, over and above the factor of twenty due to density. But such a trend does not apply uniformly over the whole range of intermediate energies; and it is a complicated matter to

determine just how the competing effects balance out in material with some particular hydrogen to uranium ratio in which neutrons of all intermediate energies are present. From the considerable reduction in critical mass effected by going to $UH_{30}$ we may assume that there is at least an appreciable component of fully moderated neutrons (with the largest fission cross sections -- and the lengthened lifetimes) in such material; and this would also be supposed from the fact that it only requires about 18 collisions with hydrogen to reduce a neutron energy to that level -- and there are thirty hydrogen atoms per uranium. However, this fully moderated component is not the dominant one, as evidenced by the further reductions in critical mass on proceeding to $UH_{100}$ and $UH_{500}$. We consequently don't know what overall factor of change in the lifetime to apply to allow for the moderation effect. We do know that the fully moderated component of the neutron population has a lifetime ten times larger than that without moderation. It would seem unlikely that any lifetime-shortening effects which might appear in other energy components of the population could result in an overall average lifetime shorter than that resulting from the density effect alone. Consequently, we shall assume a lifetime twenty times larger than that in metal at normal density. As will be seen, if the actually appropriate average lifetime should be larger than this our conclusion would be strengthened.

It has already been mentioned (in 1 f)) that the neutron lifetime appears in the term K in Serber's efficiency formula. In fact, it appears to the second power, in the denominator. An increase in the neutron lifetime by a factor of twenty will, then, lead to a four hundred-fold reduction in the efficiency estimate. For a two-crit assembly of uranium metal the energy release was about 250 tons per kilogram. From the above, a two-crit assembly of $UH_{30}$ would seem likely to have an energy release of less than a ton per kilogram.

Altogether, whether with a metal system, or a hydride system, no very effective weapon using a gun-type of assembly seems to be possible with only 12 kg of enriched uranium.

An implosion type of assembly of 12 kg of enriched uranium offers much better prospects, and several options. For example, if one sets out to obtain a two-crit supercritical result one could choose a core-reflector combination in which the critical mass was close to 12 kg and try to arrange to impose a compression factor of $\sqrt{2}$ ( = 1.4). Or one could choose a core-reflector combination with a critical mass of about 24 kg, in which case it would be necessary to impose a compression factor of two. To arrive at the most convenient pattern will obviously entail a number of possible trade-offs: including the emphasis to be placed on such considerations as the availability of beryllium, the limitations on size and weight -- both of which depend primarily on the amount of high explosive to be used, and the degree of "sophistication" within reach.

This vague term "sophistication" -- so frequently used in this connection without any indication of what may be referred to -- can, at least in part, be thought of as referring to the efficiency of transfer of energy from the HE employed to the materials to be compressed. This, along with the fact that there are options as to the modes of transfer, some of which give more favorable results than others. Such features will both be affected by the disposition of the materials of interest -- whether solid, shell, or levitated patterns.. Still, with any stated degree of sophistication, since HE will blow things in all directions, outward as well as inward, and will retain some part of the energy in its own material, the efficiency for the purpose of compressing an embedded assembly cannot be pictured as approaching a value as large as one half. and will more probably be less than one third. From published equation of state data for uranium it may be seen that the shock compression by a factor of $\sqrt{2}$ or a little more, requires that the uranium have an energy per kilogram approaching that released by a kilogram of HE. With the limitations indicated on the possible efficiency of transfer it may require about 3 kg of HE to effect this. To transfer this much energy to a core-reflector assembly of several tens of kilograms will, then, require an amount of HE in the range of a hundred kilograms. A shock

compression factor of two requires more than five times as much energy per kilogram of uranium as is needed for a compression factor of $\sqrt{2}$ Evidently very much more HE will be needed for this than the hundred kilograms or so referred to above, and -- if it can be done at all -- a considerable level of "sophistication" may be required as well.

In one way or another, then, depending on the choices made, a supercritical assembly could certainly be realized with 12 kg of enriched uranium metal in an implosion system. If the limitations which had to be observed for practical reasons -- such as on the use of beryllium, or on total weight -- were not too restrictive a two-crit assembly could be imagined. From being compressed, the neutron lifetime would be shorter than in the Hiroshima model, so the efficiency could be higher than the 250 tons per kilogram realized there, and something like a 10 KT weapon might be managed within weights (of core and reflector plus HE, only) no larger than a ton, or so. Clearly, if one adds more and more HE to the system the compression and supercriticality and potential yield will be increased; but such gains will come slowly compared to the rapid increase in weight.

One could, of course, use the 12 kg of enriched uranium as a hydride and implode that -- there is enough uranium to provide a near-critical assembly of $UH_{10}$, or two near-critical assemblies of $UH_{30}$. Such material would be somewhat more compressible than uranium metal, and that would tend to mitigate the problem discussed earlier with the neutron lifetime. But it wouldn't remove it; and apart from the possibility of having two quite small explosions (which could not be achieved with metal) there would not seem to be anything to recommend it. There is no reason to suppose that one could extend (or equal) the range of yields available from metal by taking that option. Though this possibility should not be ignored, we do not discuss it further here.

* Case B. With about 20 kg equivalent of 93% enriched uranium more options come in sight. These include the possibility of a gun-assembled device with a beryllium reflector which, depending on the reflector thickness, could constitute between 1.5 and 2 critical masses, and produce an explosion with an energy release in the range from about 100 up to possibly 200 tons per kilogram of fissile material. Similarly, implosion systems using reflectors of more familiar materials could be used to produce supercritical assemblies having two, or somewhat more, critical masses. It seems likely that the yield from one or another device of this type could be brought up to 20 KT or so. It might be possible, but would probably not seem attractive, to try to make two smaller metal devices with this amount of fissile material.

As before, it would be possible to consider implosion systems using the material in the form of hydride. There is enough material to provide two near-critical units of $UH_{10}$, or four near-critical units of $UH_{30}$. These could be compressed by a factor of about two, and possibly more. From the data at hand we are not in a position to develop a credible estimate of the yield of such objects; but by blindly following the qualitative arguments advanced in the course of the earlier discussion of what might be expected of uncompressed $UH_{30}$ one might guess that the $UH_{30}$ units (compressed two-fold) would provide yields in the range of ten to a few tens of tons and that the yield of the $UH_{10}$ units would be about ten times larger -- that is, in the range of one to a few hundred tons. No specific attention should be given to the particular numbers suggested for these yields beyond the fact that they are undoubtedly quite low on the 10 to 20 KT scale usually associated with nuclear explosions, and are something like a factor of ten apart. Whatever these yields might actually be, an option of this sort does exist. Whether it is an interesting option or not has to be left to the group making the decisions.

d) Other Considerations

The discussion above has given attention only to the matter of fissile material supply. There is a large number of other considerations which are essential to success in a weapons-building effort which have been ignored. A few of these are noted below.

* The possibility of predetonation. An adequate supply of fissile material is, of course, essential; but that is not enough. Unless its contamination with ubiquitous light elements is kept below some level which it is possible to achieve but difficult to ensure, the chance that a random neutron may result in an explosion before the intended assembly is complete may be appreciable in a gun-type model. and result in an explosion much smaller than that planned for.

* Ensuring initiation. This is not a problem in the case of a gun assembly -- at least so long as the projectile and target stay intact and in place after the assembly -- since a spontaneous fission or even a cosmic ray neutron will initiate a chain reaction in a short time. In an implosion, however, it is necessary to ensure that a chain reaction is initiated within a quite short time interval (measured in microseconds) around some designated time, and the specification of that time depends on having a very clear picture of just how one's implosion really proceeds. This is often written off by saying that one can use an external neutron generator and that such devices are commercially available. This leaves aside the question of whether the generators available come close to meeting the particular needs that one's implosion system may require. As an alternative it is often pointed out that one can use a modulated neutron source in which the alpha particles from a quantity of polonium - 210 impinge on beryllium and produce neutrons. The amount of beryllium required is quite small, and easily available, and doesn't even have to be in the form of metal. The Po-210 is sometimes also said to be readily available. The amount needed will be in the range of some number of curies -- a

curie being about two tenths of a milligram of the isotope. It exists in nature as a member of the decay chain of natural uranium, there being one curie present in every three tons of uranium. All one has to do is chemically process three tons of uranium to extract each curie required. This is not "readily available" in everyone's book. It can, of course, also be acquired -- and much more readily -- by "manufacturing" it. That is, by irradiating bismuth in the neutron flux of a small reactor. For this one needs an operating reactor. Easiest of all, perhaps, it used to be possible (and may still be) to obtain it under license from the AEC. However it is acquired it is difficult and extremely hazardous to handle; and, since Po-210 has a half-life of 138 days, unless one plans to use one's Po-Be initiator within a rather few months it will be necessary to replenish one's supply. The problem of obtaining or developing a suitable initiator is not insurmountable; but it does have to be surmounted.

* Calculations. There are situations in which one can be quite confident -- even without experimental demonstration -- that one can obtain a nuclear explosion. An example would be that of the implosion of a near-critical configuration -- at least provided there should be no gross malfunction of the assembly system. (One's confidence in the proper operation of the assembly system would, of course, be based on the observation of some number of successful test-firings.) In spite of one's confidence that a nuclear explosion would have to result, one would not know with precision what yield would be realized. Naturally, one will have tried to calculate this as well as one could; but no matter how hard one might try -- nor how fancy a computer one might have -- there will remain many points, some in the course of the assembly (compression) phase of the process and more during the exploding phase, at which assumptions will have to be made because the precise state of materials under the conditions that apply are not subject to direct and detailed observation. The combination of the effects of any departure of these assumptions from the exact state of affairs may or may not have an appreciable effect on the end result; but in any case is unknown *a priori*. Of course, after the event one can repeat the calculation and

patch it up to make it fit, and perhaps put a finger on some importamt discrepancy. But before having seen an experimental result and having thus had a chance to confirm or correct one's calculational treatment one doesn't really know the yield nor the precision of one's estimate. It may be only a few tens of percent uncertain, or a factor of a few. A new group in its first use of a nuclear weapon will be faced with some such uncertainty.

* Effort. What has been outined in this discussion relates mainly to the sort of end-products which may be feasible on the basis of fault-free work. Little or nothing has been said about the matters on which practice or experimentation may be required, nor points at which finesse may be necessary to avoid mistakes, nor with respect to hazards which must be foreseen and provided against. End-products of the sort referred to could be realized; but whether the Iraqis, or other groups, are in a position to do so is not known. It required over two years for the very large group engaged in the war-time Los Alamos project to produce an atomic explosion. There were, of course, a large number of items on which no information was available at the start of that project -- such as whether an explosion was possible, values of neutron cross sections, critical masses, uranium and plutonium chemistry and metallurgy, and others. These are now well documented and available to the public, and such work does not have to be repeated. In spite of this it should be expected that for a new project to have a device in hand a fairly large and competent staff, with diverse experience and capabilities, with all necessary bureaucratic support (but free of bureaucratic supervision), would have to work intensively for at least a year.