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A Study of Destructive Energy Released at Fast Breeder Reactor Maximum Hypothetical Accident

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A Study of Destructive Energy Released at Fast Breeder Reactor Maximum Hypothetical Accident

Summary

A computing model to calculate destructive energy release at maximum hypothetical accident, is developed in this report.

Two types of energy release, pressure wave propagation and vapor blast pressure, are considered as realistic destructive energy release, since they were demonstrated in numbers of past reactor destructive tests, and also they exist in rapid explosion, such as TNT powder explosion and chemical gas explosion.

In the computing model, acoustic impedance effect resulting from the molten core expansion is assumed for the pressure wave propagation and results of past reactor destructive tests are refered to in the vapor blast pressure calculation.

The calculations were carried out on the hypothetical accident of JEFR (Japan Experimental Fast Reator) and it is found that 8 MW-S of energy would be released by pressure wave propagation with 960 kg/cm^2 of peak pressure and that 98 MW-S of energy would be released by vapor blast pressure with 21 kg/cm^2 of equilibrium pressure. These results make good correspondence with the 1/5 scaled mock up vessel explosive test performed with 400 g TNT powder in JAERI, 1968.

Therefore, this model seems to give more realistic estimation of destructive energy released at the maximum hypothetical accident of a fast breeder reactor than those models generally used.

Aug. 1969

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高速炉の仮想事故時における破壊エネルギーの考察

要　　旨

本報告書は，液体金属冷却高速炉の仮想事故時における破壊エネルギー発生量についての，一つの計算方法について述べたものである．

これまでの原子炉破壊実験で証明されているように，原子炉の発生した破壊エネルギーの形態は，瞬間的な圧力波の放出と半静的な内圧上昇であった．これは，TNT 火薬の爆発や，高圧ガスの爆発等早い破壊エネルギー放出に共通した現象である．高速炉の仮想事故においても同様のエネルギー放出が考えられるのは当然である．

本稿の計算方法では，圧力波の発生計算には，熔融炉心の膨脹に伴なう音響インピダンス効果を用いた．また内圧上昇の計算には，これまでの実験結果から換算される破壊エネルギーの上限値が，蒸気発生に費されるとして計算を行なった．

JEFR 炉第二次概念設計を基に計算した結果，圧力波形態で放出される破壊エネルギーは，先尖圧力 960 kg/cm² を持つ 8 MW-S のエネルギー量であり，圧力上昇による放出は，最大圧力 21 kg/cm² で放出エネルギー量 98 MW-S であった．この計算結果は，TNT 火薬を用いて行なったモックアップによる耐爆実験の測定結果とよく一致している．

これらのことから，本稿の手法による計算は，これまで普通行なわれている計算方法に比較して，より現実的で妥当な結果を示すものと思われる．

1969 年 8 月

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1. Introduction

In the course of fast reactor safety analysis to date, it is traditional to consider the gross melting and consequential compaction of the core which makes the reactor prompt critical.

Although there are many ways to bring about this situation, the accident is considered to commence when the coolant sodium is lost from some part or whole of the reactor core while the reactor is operating at power*[37]. Because of the loss of coolant, the reactor fuel is heated and melted, then it flows down to the bottom of the core where the melted fuel accumulates. Since the fuel is compacted in smaller volume and the fuel density becomes higher, the reactor reaches prompt critical with rapid rate of reactivity insertion which is determined by the fuel melting rate. When the reactor becomes prompt critical the reactor power increases very rapidly because of small prompt neutron life time in fast reactors. This accident is only terminated by explosive disassembly of the core. This course of accident has been taken as the maximum hypothetical accident in fast reactors and the method to analyze it was first developed by Bethe and Tait. There have been many improvements in the treatment, and they are called the modified Bethe-Tait methods. Original Bethe-Tait method treated the accident under the following assumptions[2].

(1) Reactivity insertion is step.

(2) The pressure is a function of internal energy (temperature) only.

(3) The saturated vapor pressure of molten fuel is not considered.

The third assumption is the reason that the equation of state is called threshold type. (threshould medel)

(4) The reactivity feed back by core disassembly is treated by perturbation treatment.

In many cases, caluculations to analyse the behavior of the core in this type of accident are done by AX-1 code or similar codes, in which reactivity feed back is calculated more precisely. Usually the following assumptions are made to determine the rate of reactivity insertion.

(5) The loss of coolant occurs instaneously.

(6) Molten fuel falls down to the bottom of the core with gravitation.

(7) Feed back considered other than the core disassemly is the Doppler effect only. To make the assumption conservative, the Doppler coefficient is taken to be half the calculated value.

The calculation of the hypothetical accident analysis for JEFR was carried out based on the above mentioned assumptions[2]. **(Fig. 1)**

According to the threshold model, at the time when the core disassembly takes place, about 10 k bar of pressure is generated during 10^{-4} second of time interval. The reason is that because of assumption (3) the pressure which causes core disassembly is generated only after the voided space is occupied by molten fuel.

The assumption of threshold model, together with the assumption of instantaneous and complete loss of coolant[3),4),5)], has been considered to be unrealistically severe and the equation of state which takes into account saturated vapor pressure of molten fuel (vapor pressure model) will be employed as more realistic model[3),4),6),7)].

According to the saturated vapor pressure model, the maximum pressure in the core becomes more than one order smaller than in the case where threshold model is employed. Also the pressure rise time is slowed down to about 1 millisecond.

* There is a possibility that fuel melting occurs by decay heat; however, if the reactor fuel is not metallic one, the reactivity insertion rate introduced by this melting should be very slow.

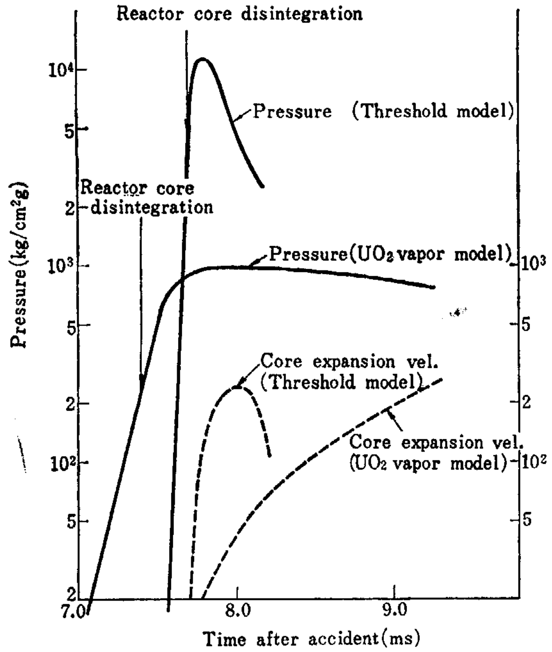


Fig. 1 Comparison of M.H.A. analitical results between threshold model and UO_2 vapor model. (300 l PuO_2-UO_2 core)

This result is not much different from the results obtained in the destructive tests carried out on the reactors such as SPERT and SNAPTRAN[10),11),12),14),15),16),17),37)].

According to the saturated vapor pressure model, the total energy generated during the accident can be calculated, however, the work to be done by that amount of energy cannot be uniquely determined in contrast with the case of threshold model.

When the threshold model is employed, the upper limit of the destructive energy $E_{k\,max}$ is determined as

$$E_{k\,max}=\int\rho(E-E^*)dv$$

$$E-E^*\geq 0$$

where E is the energy density

E^* is the threshold energy density beyond which the pressure is generated.

ρ is the density of the core material.

Since the pressure generated by this energy is in the order of $10^4\,kg/cm^2g$ and since the time duration of this pressure is very short, it is expected that the pressure vessel of the reactor may be destroyed when this psessure is released. Therefore, the work done by the vapor blast pressure which is generated through heat transfer after the pressure wave is released is considered not to work as destructive energy, because it works in wider space after the pressure vessel is destroyed. That is, according to the threshold model, the destructive energy release is in the form of pressure wave propagation and energy release in other form is not the destructive energy release.

On the other hand, to calculate the destructive energy in the saturated vapor pressure model, it is necessary to calculate the internal energy of UO_2 vapor correctly during the accident. Also, considering the long time-interval of the energy release in the saturated vapor pressure model, there arises a question whether the destructive energy in the form of pressure wave propagation is only the form of destructive energy as in the case of threshold model. And, as found in the past experiment, the heat transfer from the molton fuel to the coolant which exists near the fuel causes sudden boiling of some of the coolant, which becomes large source of destructive energy[20)].

Therefore, the estimation of destructive energy release becomes more complex in the saturated vapor pressure model. Those who insist on the adequacy of the saturated vapor pressure model usually do not mention about the estimation of the destructive energy release converted from the total energy. They just make parametric calculations for the behavior of core pressure or the total energy release and discuss the inadequacy of the threshold model[3),4),5)].

However, when it comes to the design and construction of fast reactors, these two models give drastic difference in design phylosophy. The reactor vessel of a fast reactor is designed to be broken when such a hypothetical accident takes place, however, blast shield which surrounds the reactor vessel must not be broken[18)]. Whether the peak pressure of the pressure wave is 10,000 kg/cm^{2}g as in the threshold model or it is 1,000 kg/cm^{2}g as in the saturated vapor pressure model gives very large difference both in the design specification and in the construction cost. If the blast pressure of sodium vapor have to be added to the above mentioned pressure wave, it is necessary to pay more attention to the design of the upper shield and the structures around the reactor vessel, which might be damaged with blast pressure.

One of the methods to estimate the structural integrity which accomodates the hypothetical energy release is to make a mock-up experiment with high explosive which has higher destructive energy than that of hypothetical accident[6),7),19),34),35)].

High explosive releases about a half of its energy as in the form of shock wave* and its peak pressure is 10~100 times larger than that of the pressure wave generated in fast reactor hypothetical accidents. Therefore, as long as the shock wave is concerned, proof test by high explosive will give satisfactory answer for safety[18),34),35)].

On the otherhand, half of its total energy is released in the form of expansion of high temperature gas, which corresponds to the blast pressure of sodium vapor[19),35)].

However, in the past mock up experiment, the quantity of the high explosive was determined so that the total energy of the explosive might be equal to that released during the hypothetical accident without considering the form of energy release such as the shock wave or the blast pressure. Therefore, some questions have arisen for the experiment carried out in the past.

For instance, since the form of energy released from the threshold model is pressure wave propagation only, it shoud correspond to the energy of shock wave in the high explosive experiment. Based on the above descussion, the quantity of high explosive should be determined so that the shock wave energy of the high explosive might be equal to that of the pressure wave in the hypothetical accident.

In this case, the quantity of high explosive necessary for the experiment is doubled, compared with the case when the quantity of the high explosive is determined so that the total energy of high explosive is equal to the total energy release.

Having studied the destructive energy release, questions concerning the past experimental basis, in which the quantity of high explosive is determined so that the total energy might be equal, have naturally arisen.

The purpose of this report is to try to make the form of energy release clear in the fast reactor hypothetical accident, and thus to try to make the hypothetical energy release in JEFR correspond to the mock up test using high explosive.

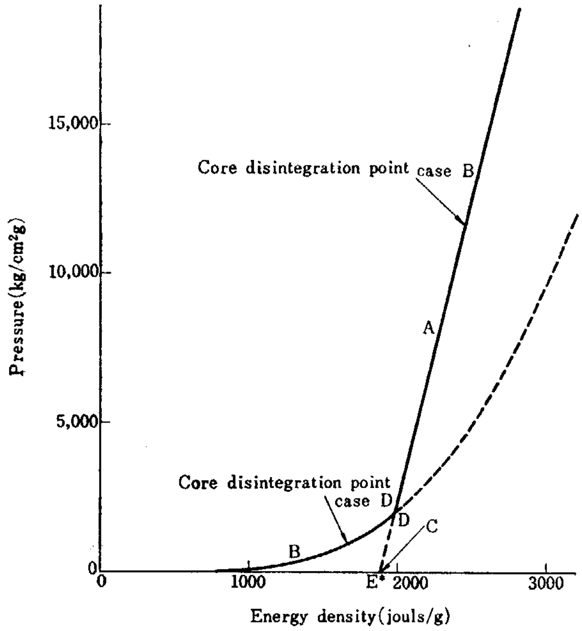
The accident phenomena which are the bases of our calculation will be discussed in the next section.

---

* To distinguish the difference in energy release between the high explosive and the reactor destruction, in this report, the initial pressure wave propagation of the explosion of high explosive is called shock wave and that of the reactor explosive disassembly is called pressure wave. In the same way, the work done by the expansion of gas of high explosive is called blast pressure of gas and that of the reactor is called blast pressure of sodium.

2. Comparison of the Calculated Result of the Two Models

As we have mentioned, there are two calculational models (the threshold model and the saturated vapor pressure model) depending on whether the vapor pressure of molten fuel is taken into account or not. **Fig. 2** shows the two equations of state used in the calculations which represent the pressure as a function of internal energy of UO_2. (In the figure, curve A represents the threshold type equation of state; the pressure is generated after the internal energy of UO_2 exceeds threshold value C. Curve B represents saturated vapor pressure type equation of state; in this case cartain vapor pressure exists after the internal energy exceeds melting point of UO_2.)



A: Threshold type equation of state
B: UO_2 vapour pressure model

Fig. 2 Equation of state for UO_2
Critical constants of UO_2
$T_c = 8,000$°K
$P_c = 2,000$ kg/cm²g
$Z_c = 0.27$

The calculations for JEFR hypothetical accident were carried out for the next four cases with the above mentioned equations of state.

(1) Case A 300 *l* P_uO_2 fuelled core; threshold model
(2) Case B 300 *l* P_uO_2-U^EO_2** fuelled core; threshold model
(3) Case C 300 *l* P_uO_2 fuelled core; saturated vapor pressure model
(4) Case D 300 *l* P_uO_2-U^EO_2 fuelled core; saturated vapor pressure model

The calculations were carried out by AX-1 code with the same assumptions other than the equation of state[2]. When the same equation of state is used (between case A and B, or between case C and D) in spite of the difference in core materials, they give similar result. On the other-hand, when the different equation of state is used for the same core, the following differences are found. For instance, if we take case B and D, peak power and the total generated energy during the accident differ about 50% each other. The reason is that when the saturated vapor pressure model is used, UO_2 vapor pressure is generated even before the fuel reaches its boiling point, and that it expands the core, and to compensate the inserted reactivity although the pressure is relatively low. On the otherhand when the threshold model is used, feed back by core expansion (disassembly) cannot exist until the fuel teamperature reaches its threshold value. Arrows shown in **Fig. 2** represent the UO_2 vapor pressure at the time when the core disassembly takes place for each case. It explains the situation stated above. This is also the reason for the large difference in the maximum core pressure between case B and case D.

Therefore, as we have mentioned in section one, the results of the analysis carried out with these two models would differ significantly from each other. In **Fig. 3a**, **3b** and **4** the results of the calculations of case B and case D are shown.

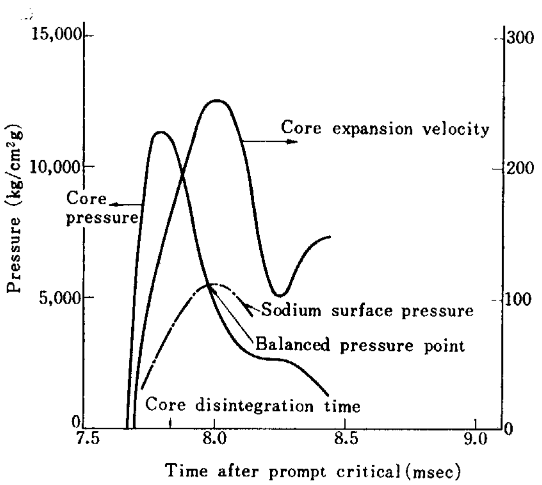


Fig. 3a M.H.A. calculation results by AX-1 code (Threshold model case-B)

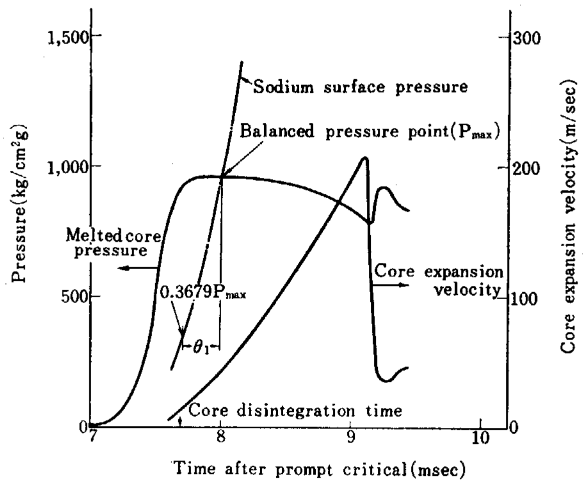
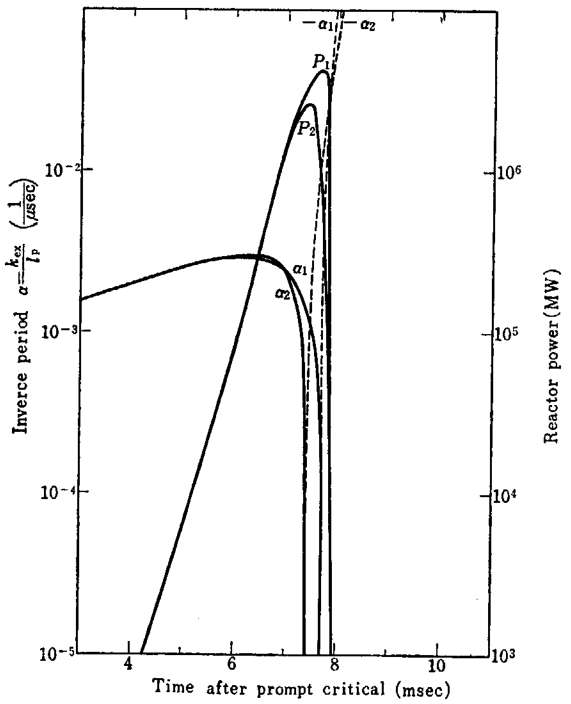


Fig. 3b M.H.A. caluculation results by AX-1 code (Vapour pressure model case-D)



P_1, α_1: Threshold model
P_2, α_2: Vapor pressure model
Fig. 4 M.H.A. calculation results

** U^E denotes 20% enriched uranium.

3. Calculation Model of the Destructive Energy of the Maximum Hypothetical Accident

The discussion of the former section shows that the threshold model yields extremely conservative results on the maximum hypothetical accident analysis and that questions for the threshold model have widely arisen.

As a matter of fact, a number of past reactor destructive test results carried out for both light water reactors and liquid metal cooled reactors have demonstrated that the reactor destructive energy are not so large as that computed from the threshold model and that most of the destructive energy was in form of blast pressure generated with vapor bubble expansion[9),10),11),12),13),14),15),16),17),20)]. For these reasons, the use of the threshold model and the need for some modifications on the model are being gradually understood. Therefore in this section only the saturated vapor pressure model is discussed in detail to study the two forms of destructive energy release: pressure wave propagation and vapor blast pressure.

3.1 Pressure Wave

Recall the starting point of the hypothetical accident based on current assumption of modified Bathe-Tait model. Coolant is perfectly ejected from some part of whole of the core and core fuel start melting by lack of coolent. Melted fuel flows down and is accumulated in the lower part of the core and thus the reactor reaches prompt critical.

Once prompt criticality is established, the system, coupled with the melted core and unmelted core, generates significant amount of excursion power during the system in prompt criticality. The energy of the excursion power is used in two ways. A part of it is used for increasing fuel temperature, and the other is for generating fuel vapor in the melted core. Temperature rise increases fuel melting rate and fuel vapor increases the melted core pressure which expands the melted core. The system temperature rise also increases Doppler feed back. These two effects decrease reactivity and thus the system becomes subcritical finally. In the saturated vapor pressure model excursion energy is less, since the melted core expansion begins at an earlier stage of excursion and compensates for certain amount of reactivity. However, in the threshold model, the core does not expand until the voided space is occupied by molted fuel.

The above discussion is supported by the calculated results in **Fig. 3a**, **3b** and **4** (all the results were obtained from the AX-1 calculation).

After the power burst is terminated, the highly pressurized melted core still exists and it keeps expansion as shown in **Fig. 5**. It seems that the core expansion becomes rather violent after

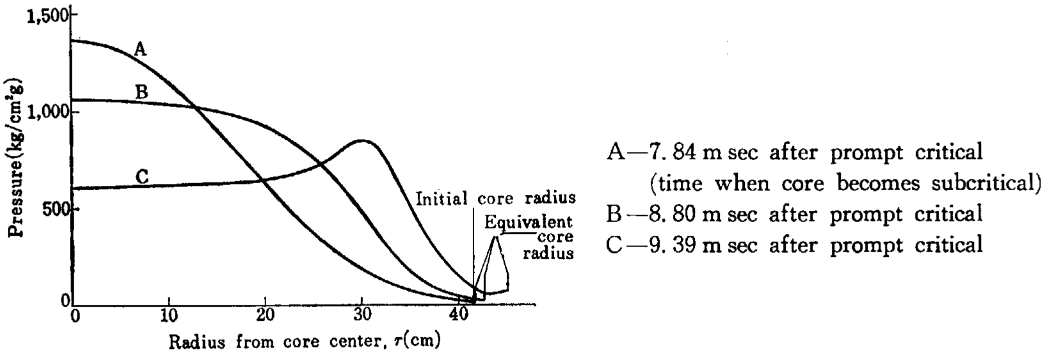


Fig. 5 Pressure distribution of melted core

termination of power burst, since the pressure of outer edge of the melted core increases with time.

From the assumption of the hypothetical accident, coolant is perfectly lost from the core; however, coolant is still left in the periphery of the core, such as blanket, upper plenum and lower plenum. Accompanied by the expansion of the melted core, its surface begins to contact with the coolant left at core periphery, and pushes the coolant outward. Once coolant is moved, coolant surface is pressurized by the acoustic effect and the pressure is propagated through the coolant. If the velocity of the surface movement is small, the build up pressure on the coolant surface is also small and propagated pressure is rather weak, as observed in usual boiling phenomena. However, if the moving velocity is large, the build up pressure can propagate in short distance from the coolant surface and only a part of the coolant around the melted core is pressurized. Therefore, pressure propagation would be a type of pressure pulse or pressure wave to the outer system.

Such a rapid core expansion will be kept for short period and it should be terminated when the coolant surface pressure is equal to the melted core surface pressure. Then the maximum pressure of the pressure wave should be the balanced pressure at both surfaces.

The dotted lines in **Fig. 3a** and **Fig. 3b** indicate the pressure at the coolant surface which is calculated with above acoustic effect. The point where the two pressure, core pressure and coolant surface pressure, cross, is then the maximum pressure of the pressure wave propagated into the outer system. Thus the results of **Fig. 3b**, shows that the maximum pressure is 960 kg/cm^2 g and time constant of increasing pressure is about 0.15^{ms} (Ref. to 4. 2. 1). Accordingly propagation distance of the pressure wave at the time of the maximum pressure is only 9^{mm} from the coolant surface. Therefore, these computed data support the phenomenal analysis of pressure wave generation discussed above.

After the peak pressure is attained, two models will be considered to analyse decreasing pressure wave. In the first model the melted core expands keeping a pressure balance at the boundary surfaces, though the core expansion velocity under this condition might be slower, and thus the build up pressure on the coolant surface becomes smaller.

If it is assumed that the rapid core expansion velocity is still kept with the pressure balance, the pressure balance on the boundary surfaces would be broken, since the coolant wall pressure should be equal to the maximum pressure, but on the contrary the melted core pressure should be decreased with core expansion. (It must be noticed that burst power is already terminated and

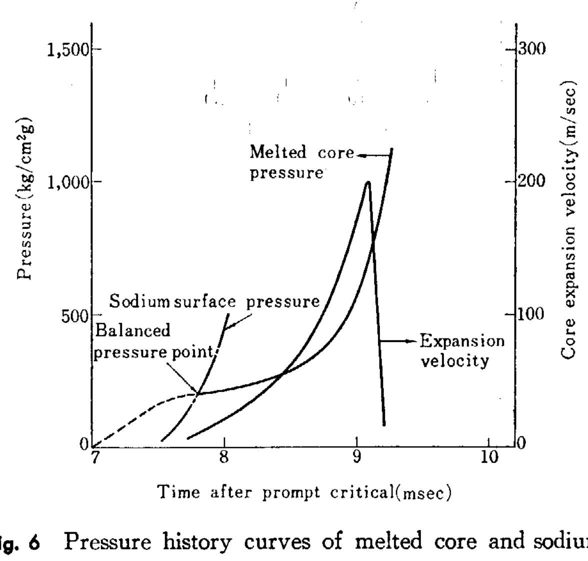


Fig. 6 Pressure history curves of melted core and sodium surface at 30 cm radius model (PuO_2-U^EO_2 core)

no energy is generated in this stage.) Once pressure balance is broken, cold coolant would rush into the hot expanding core. In this case, violent heat transfer is expected between hot melted core and cold coolant. This is the second model to be considered.

Even in the first case, it is true that heat transfer at the boundary surface must be considered[3),4),20)]. Temperature difference between the melted core and the coolant at the boundary surface is very large, and some heat transfer from the melted core to the coolant is expected. In either model, since this heat transfer takes some heat from the melted core, pressure of the melted core with heat transfer should become smaller. The steam generation with this heat transfer will be discussed in section 3. 2.

However, adequate heat transfer estimation is too complex to analyse under such a condition and thus, in the calculation model for the decresing pressure of the pressure wave, isothermal polytropic expansion assumption is adopted in the first model. Since this polytropic assumption computes slower decreasing pressure rate as discussed above, the results would be rather conservative.

Detailed computation procedure of isothermal polytropic expansion is described in the section 4. 2 (Eq-12). The computed result shows that the time constant of decreasing pressure wave is approximately 1.55^{ms} (in **Fig. 3b**). Since maximum pressure and time constants are obtained, pressure wave energy is now computed. Approximately 8 MW-S of pressure wave energy is computed from Eq. 7 in section 4. 1. The computed pressure wave is shown in **Fig. 7**.

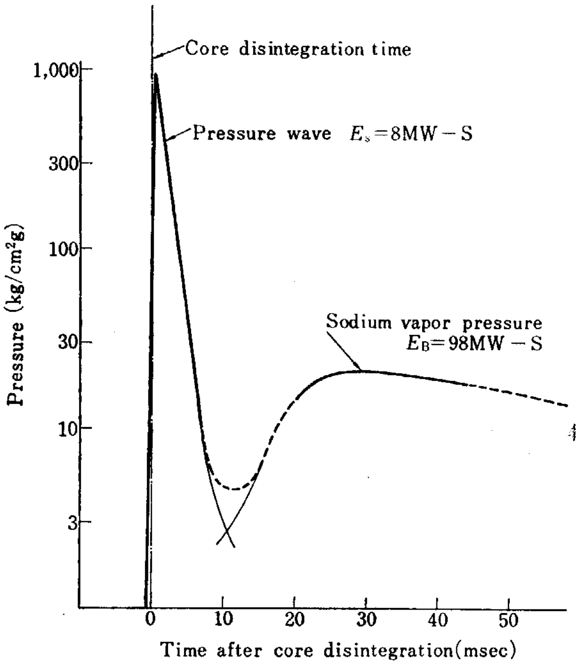


Fig. 7 Estimated pressure generation of JEFR reactor at M.H.A.

Although conservative assumptions are used in the calculation, both the maximum pressure and the released energy of the pressure wave which are computed from the newly developed model, are well below the results obtained by currently used computing model. Also it must be noted that the pressure wave energy is approximately ten times larger than that of past reactor destructive experiments. Therefore, the newly developed model seems to give reasonable pressure wave calculation in the hypothetical accident evaluation.

The same procedure is used on the threshold model just for examination. It is computed that the peak pressure of 5,400 kg/cm^2 with 120 MW-S of energy would be released within 0.8 ms. It is interesting that the 120 MW-S of energy relatively well agrees with the 160 MW-S which is computed with the current method, as stated in Section-1. And again, it must be emphasized that there is significant difference in pressure wave energy between the saturated vapor pressure model and the threshold model, 8 MW-S and 120 MS-S, respectively.

3.2 Blast Pressure

After the pressure wave is released, the melted core still expands until the whole system pressure becomes equilibrium. For the calculation of this stage, heat transfer have to be considered.

Past reactor destructive experiments on the light water reactors[10),11),12),13),14),37)] and the liquid metal cooled reactors[15),16),17)] such as, SPERT, BORAX and SNATRAN, demonstrated that more than half of the destructive energy was released as the blast pressure which is considered to be generated with vapor expansion[10),11),20),21),22)]. Heat source to generate vapor was heat transfer from the ruptured fuel meat to the coolant. However, detailed mechanism of this heat transfer is too complex and many unknown factors are combined together, such as, how much heat is transfered to the coolant in certain time duration, how much coolant is evaporated at that time and so on. Let us examine power excursion energy which generates vapor at first. Assuming that all the excursion energy is evenly transfered to all the coolant of JEFR reactor, sodium temperature rise is approximately 60°C and maximum coolant temperature is about 610°C in this case. It is far below the liquid sodium boiling temperature, 881°C. No vapor is generated in this condition. Only way to assess vapor generation problem is to use past experimental results.

Blast pressure is considered to be generated by evaporation of coolant which contacted with hot fuel[20)]. Once vapor is generated through violent heat transfer, pressure wave is generated by their rapid expansion and blast pressure is induced later by their growth. Both pressures work as destructive energy.

Recent SPERT-CDC data demonstrate that approximately 2.5 per cent of total energy was converted into both destructive energies. Five per cent of converting ratio is chosen in this calculation. The ratio is more than two times larger than the actual one. Computed results show that the maximum blast pressure is 21 kg/cm^2, and that the blast pressure energy is about 98 MW-S (Ref. 4.3).

Additonal problem occurs when blast pressure works in the system effectively. There is no effective approach for this problem. In the calculation, conservative but practical approach is used, that the melted core expansion speed is kept at its maximum velocity (44 M/S). The time when the melted core expands to the total gas plenum, (approximately 6 M^3) which exists in the upper part of the reactor vessel, is assumed to be the time that the maximum blast pressure is reached. It is about 28 ms after the maximum peak pressure of pressure wave. It is also in good agreement with the SL-1 accident analysis in which accident water slugs beat upper pressure vessel 34 ms after the peak power, with 159 ft/sec velocity.

All the calculation results are shown in **Fig. 7**. The dotted lines indicate the value guessed from computed results. The maximum pressure of the pressure wave is about 960 kg/cm^2, and time constant of increasing pressure wave is 0.15 ms and that of decreasing pressure wave is 1.55 ms. This large time constant of decreasing pressure wave is typical in pressure wave or shock wave, as observed in TNT powder explosion. It is noticed that the maximum pressure of the pressure wave appears after the core disintegration (time that the core becomes subcritical). Energy release by the pressure wave is approximately 8 MW-S which is larger than the past destructive test results, but is not so unrealistic as the results of current computing models.

The blast pressure which is generated with vapor expansion releases approximately 98 MW-S of energy after the pressure wave is released. This time duration is about 28 ms. The maximum pressure of the blast pressure is approximately 21 kg/cm^2. These data also agree with past experimental results[9),10),11)].

A valley between the pressure wave and the blast pressure is difficult to compute. Perhaps, there are scores of pressure oscillations in this area as demonstrated in SPERT experiments. However, peak values of these pressure oscillations should be much smaller than that of the initial pressure wave, since the system compressibility is increased by vapor which is generated by heat transfer from the melted core during the first release of pressure wave. Therefore, energy release with these pressure oscillations may be relatively small and it is well compensated with the conservative calculations of the blast pressure energy.

These calculations are developed based on the computed results of the AX-1 code, in which free expansion is assumed in the melted core expansion. Therefore, the pressure of the melted core surface is always equal to the atmospheric pressure, as shown in **Fig. 6**. A compromise that the core average pressure is the surface pressure, is used for the pressure wave calculation in this report.

If a reasonable equation of state could be given to the coolant materials which contact to the melted core, the code AX-1 should compute accurate coolant movement velocity and pressure wave propagation. However, it may not be possible to provide a reasonable equation of state in such a system that coolant, fuel and components are mixed together.

Thus the compromization was used to compute actually the pressure wave.

4. Calculation and Results

4.1 Destructive Energy by the Pressure Wave

When the gas in the liquid is expanded, the pressure at the boundary of two media $P(t)$ is expressed with the acoustic impedance Z^* and the expansion velocity of the gas $V(t)$ in the following equation:

$$P(t)=Z\cdot V(t) \tag{1}$$

and

$$Z=\rho\cdot c$$

where

ρ: Density of surrounding medium

c: Sonic velocity in the medium

Pressure $P(t)$ is approximated by the exponential function:

$$p(t)=P_{\max}e^{-t/\theta} \tag{3}$$

where $P_{\max}$: Maximum pressure

θ : Time constant of pressure wave

The energy $E(t)$, which is delivered to the medium by the expansion of the gas, during the time interval Δt, is

$$E(t)=4\pi\int P(t)\cdot V(t)\,r(t)^2\,dt \tag{4}$$

where $r(t)$: radius of gas bubble at time t

In general, the time interval of energy release with shock wave or pressure wave is extremely short, and thus the displacement of the gas bubble surface is small. Therefore, the gas bubble radius $r(t)$ can be taken to be its initial value r_0.

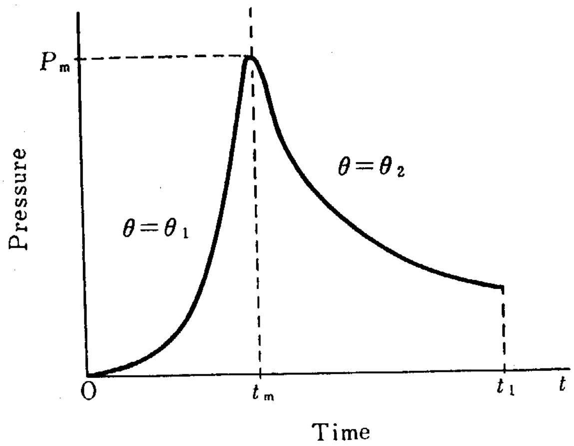


Fig. 8 Pressure pulse shape.

Now, we consider the form of pressure wave as expressed in **Fig. 8**. Θ_1 and Θ_2 are the time constants of increasing and decreasing pressure wave respectively. Initial time (t_0) is defined as the time when the pressure respectively. Initial time (t_0) is defined as the time when the pressure begins to generate, t_m is the time corresponding to the maximum pressure (P_m) of the pressure wave, and t_1 is the arbitrary time after that effective pressure wave energy release is lost.

Substituting (3) and (4) into (1), one obtains the expression for the increasing pressure wave ($t<t_m$),

$$E_{\Theta_1}(t)=\frac{4\pi r_0^2}{Z}P^2{}_{\max}\int_0^{t_m} e^{-\frac{2(t_m-t)}{\Theta_1}}dt$$

and for the decreasing pressure wave ($t>t_m$),

$$E_{\Theta_2}(t)=\frac{4\pi r_0^2}{Z}P^2{}_{\max}\int_{t_m}^{t_1} e^{-\frac{2(t_m-t)}{\Theta_1}}dt$$

Then the total energy $E(_{t_1})$ of the pressure wave, generated by time t_1, is

$$\begin{aligned}E(t)&=E_{\Theta_1}(t)+E_{\Theta_2}(t)\\&=\frac{4\pi r_0^2}{Z}P^2{}_{\max}\left\{\int_0^{t_m} e^{-\frac{2(t_m-t)}{\Theta_1}}dt+\int_{t_m}^{t_1} e^{-\frac{2(t_m-t)}{\Theta_1}}dt\right\}\\&=\frac{4\pi r_0^2}{Z}P^2{}_{\max}\left\{\frac{\Theta_1}{2}(1-e^{-\frac{2t_m}{\Theta_1}})-\frac{\Theta^2}{2}(e^{-\frac{2(t_1-t_m)}{\Theta_2}}-1)\right\}\\&=\frac{2\pi r_0^2}{Z}P^2{}_{\max}\left\{(\Theta_1+\Theta_2)-(\Theta_1 e^{-\frac{2t_m}{\Theta_1}}+\Theta_2 e^{-\frac{2(t_1-t_m)}{\Theta_2}})\right\}\end{aligned}$$

Total pressure wave energy $E(t_1)$ can be conservatively calculated by (7), since $2t_m\gg\Theta_1$ generally and $2(t_1-t_m)\gg\Theta_2$ when we take t_1 large enough.

$$E(t_1)=\frac{2\pi r_0^2 P^2{}_{\max}}{Z}(\Theta_1+\Theta_2) \qquad (7)$$

where

$P_{\max}=960$ kg/cm² g	(c.f. **Fig. 4a**)
$r_0=42$ cm	(c.f. **Fig. 5**)
$Z=0.223$ kg-s/cm³	(calculated at 250°C for sodium)
$\Theta_1=0.15$ ms	(c.f. Section 4. 2. 1)
$\Theta_2=1.55$ ms	(c.f. Section 4. 2. 1)

Putting above constants into (7), $E(t_1)$ is calculated to be

$$\begin{aligned}E(t_1)&=8.04\times10^5\ \text{kg-m}\\&=7.9\ \text{MW-S}\end{aligned}$$

Hence, pressure wave would release at most 8 MW-S of destructive energy by the calculation.

Pressure wave with threshold equation of state is calculated in the same manner and resulted in the energy release of about 120 MW-S (P_{max}=5,400 kg/cm^{2}g, $\Theta_1+\Theta_2$=0.8 ms), and it is interesting that this value 120 MW-S relatively well agrees with the result in **TABLE 1** (160 MW-S).

Fig. 9 shows the relationship between pressure and velocity at the boundary surface of gas ball in the sodium.

TABLE 1 Calculation results of JEFR M. H. A.

	Total energy generation	Max. core pressure	Max. power	Core disintegration time	Max. energy release		
					Total	Shock wave	Vapor exp.
	MW-S	kg/cm^{2}g	MW	ms	MW-S	MW-S	MW-S
Case A	2800	12, 000	3.3×10^6	8. 06	130	130	0
Case B	3100	11, 600	4.3×10^6	7. 70	160	160	0
Case C	1600	605	2.0×10^6	7. 90	—	—	80
Case D	1970	960	2.7×10^6	7. 65	106	8	98

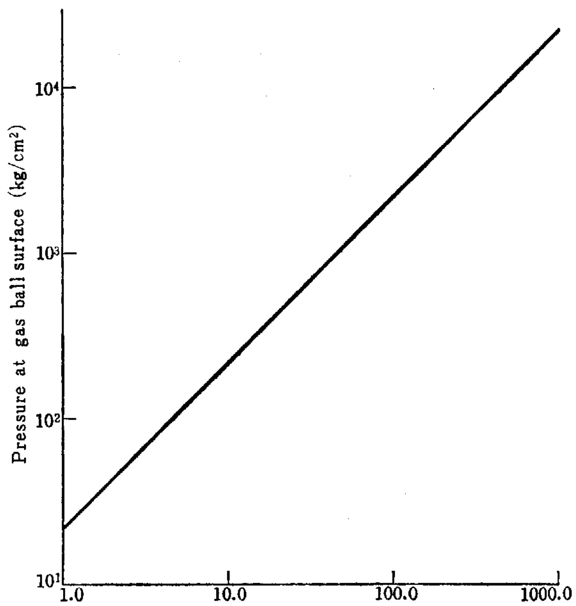


Fig. 9 Pressure-velocity relation at boundary surface of gas ball in sodium media
$P=ZV$
Z: accoustic impedance
(0. 223 kg-s/cm^3 in sodium media.)

4. 2 Time Constants of Pressure Wave

4. 2. 1 Time constant of increasing pressure wave (Calculation of Θ_1)

From the equation (3), it follows

$$e^{-\frac{t_m-t_1}{\Theta_1}}=\frac{P(t_1)}{P_{max}} \qquad (3')$$

Choosing t_1 so that t_m-t_1 is equal to Θ_1, (3′) becomes

$$\frac{P(t_1)}{P_{max}}=e^{-1}=\frac{2.7182}{1}=0.3679$$

Time constant Θ_1 can be calculated from such time t_1 that $P(t_1)$ becomes 0.3679 P_{max}. And the time t_1 is obtained from the pressure curve in **Fig. 3b**. Time constant Θ_1 is then calculated to be 0.15 ms.

4. 2. 2 Time constant of decreasing pressure wave (Calculation of Θ_2)

Supposing polytropic expansion of gas ball, one obtains

$$P\cdot v^k = \text{Constant} \tag{8}$$

On the assumption that the volume of the core (ΔV) is proportional to the specific volume change of the gas (ΔV), (8) becomes

$$P\cdot V^k = \text{Constant} \tag{9}$$

Differentiating (9),

$$\frac{dP}{dt}V^k + k\cdot P\cdot V^{k-1}\frac{dV}{dt} = 0$$

then,

$$\frac{\frac{dP}{dt}}{P} = -k\frac{\frac{dV}{dt}}{V} \tag{10}$$

Substituting gas sphere volume $V=4/3\,\pi r^3$ in (10),

$$\frac{\frac{dP}{dt}}{P} = -4k\frac{\frac{dr}{dt}}{r} \tag{11}$$

With the assumption of (3), $P(t)$ is equal to $P_{max}e^{-\frac{(t-t_m)}{\Theta_2}}$, at near the peak pressure of the pressure wave, at (11) can be rearranged in the following form, supposing $P(t)$ is equal to P_{max}

$$\Theta_2 = \frac{r(t_{max})}{4kv(t_{max})} \tag{12}$$

Now the constants of (12) are

$K=1.4$ (value for perfect gas)*

$r(t_{max})=0.42$ m (molten core radius, c.f. **Fig. 5**)

$v(t_{max})=44$ m/sec (c.f. **Fig. 4. 1**)

Putting above constants into (12), Θ_2 is caluculated to be 1.55 m/sec.

Fig. 10 shows the time behavior of the pressure wave calculated by above procedure.

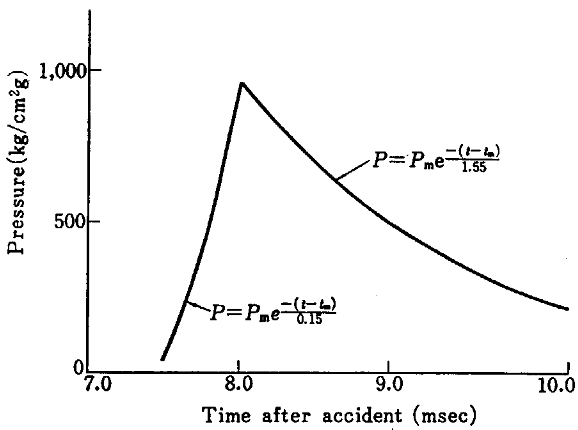


Fig. 10 Calculated pressure history at boundary surface of sodium media. (PuO_2-UO_2 core)

* Peak pressure. $P_m=960$ kg/cm³
Peak pressure time $T_m=8.1$ ms

4. 3 Calculation of Blast Pressure

Blast pressure which is supposed to be generated by the sodium gas expansion with the instantaneous heat transfer from molten fuel to liquid sodium will be calculated in the following procedure. Liquid sodium is assumed to be in saturated condition. From the conservation law of energy, one obtains,

$$h_{g_1}\cdot G_{g_1}+h_{l_1}\cdot G_{l_1}+E_B=h_{g_2}\cdot G_{g_2}+h_{l_2}\cdot G_{l_2} \tag{13}$$

where E_B is the energy transfered to sodium.

From the conservation law of mass, it follows:

$$G_{g_1}+G_{l_1}=G_{g_2}+G_{l_2}=G$$

and here g is defined as

$$g=G_{g_2}-G_{g_1}=G_{l_1}-G_{l_2} \tag{14}$$

Since the volum that gas can occupy in a vessel is limited and constant,

$$v_{g_1}\cdot G_{g_1}+v_{l_1}\cdot G_{l_1}=v_{g_2}\cdot G_{g_2}+v_{l_2}\cdot G_{l_2}=V \tag{15}$$

Since specific volume of liquid is relatively independent of pressure, both v_{l_1} and v_{l_2} are equally expressed to be v_l, and using (2) equations (13) and (14) are rearranged as follows:

$$E_B=g\cdot \Delta h_{gl}+G_{g_1}(h_{g_2}-h_{g_1})+G_{l_1}(h_{l_2}-h_{l_1}) \tag{16}$$

$$g=\frac{v_{g_1}-v_{g_2}}{v_{g_2}-v_l}\cdot G_{g_1} \tag{17}$$

In the equation (16), the first term on the right-hand side expresses the energy used for the evaporation of the sodium, the second term gives the increase in heat capacity by the compression of the saturated sodium gas, and the third term means the increase in heat capacity by the compression of the saturated liquid sodium.

Initial pressure for the calculation is taken to be atmospheric and other initial conditions are obtained from the design data of JEFR (Japan Experimental Fast Reactor, 100 MW).

Thermophysical Properties of sodium[31] shows that the heat capacity of saturated sodium vapor is relatively indenpendent of pressure, and the rate is about $-0.2\%/\mathrm{kg/cm^2}$. Therefore, the second term of (16) can be neglected. Although the third term is relatively large, we neglect the term, since the pressure change is very rapid, and 95 per cent of energy is assumed to be used for the heating of sodium. In the equation (17), v_l is relatively small and is neglected. Thus simplified (16) and (17) yeild (18), a function of V_{g_2}, to calculate the relationship between destructive energy (E) and expansion pressure.

$$\begin{aligned} E_B&=\Delta h_{gl}\cdot\left(\frac{v_{g_1}-v_{g_2}}{v_{g_2}}\right)\cdot G_{g_1}\\ &=\Delta h_{gl}\cdot G_{g_1}\cdot(x-1) \end{aligned} \tag{18}$$

$$x=\frac{v_{g_1}}{v_{g_2}}$$

Fig. 11 shows pressure-specific volume relationship of saturated sodium vapor.

Fig. 12 expresses blast pressure-destructive enegry relationshoip calulated from **Fig. 11** for JEFR. According to **Fig. 12**, about 21 kg/cm² g of maximum blast pressure is obtained from 98 MW-S of destructive energy.

Notation

In Section 4. 1		P_{max} ;	Maximum pressure
C ;	Sonic velocity	$r(t)$;	Core radius
$E(t)$;	Energy	r_0 ;	Initial core radius
$P(t)$;	Pressure	t ;	Time

t_m	;	Time at P_{max}
$V(t)$	;	Core expansion velocity
Z	;	Accoustic Impeance
ρ	;	Density
Θ	;	Time constant

In Section 4.2

p	;	Core pressure
v	;	Specific volume of core
k	;	Poly torop constant
V	;	Core volume
r	;	Core radius
$v(t)$	;	Core expansion speed

In Section 4.3

h	;	Enthalpy
G	;	Mass

(Sufix)

g	;	gass
l	;	liquid
1	;	initial condition
2	;	final condition
E	;	Energy
P	;	Pressure

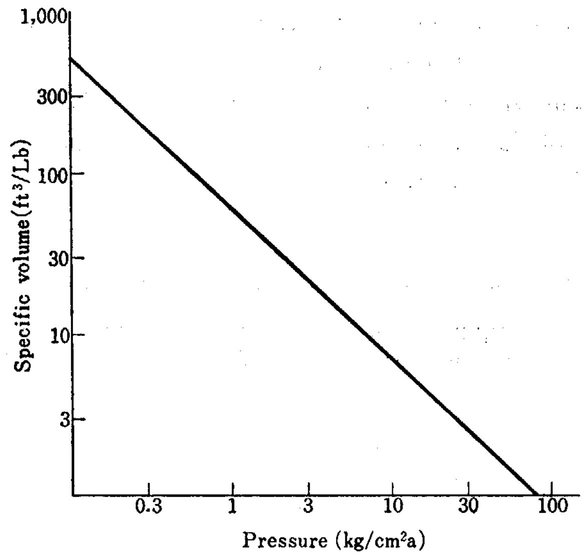


Fig. 11 Pressure—Specitic volume relationship of saturated sodium vapor

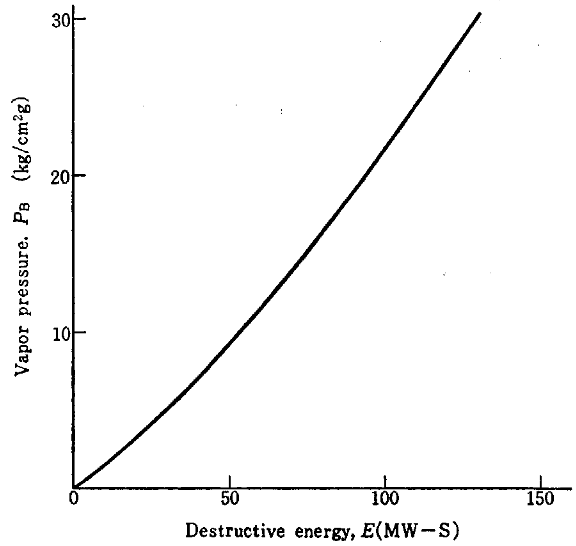


Fig. 12 Vapor pressure—Destructive energy relationship in JEFR reactor

5. Conclusion

An analysis of the accident phenomena in fast reactor hypothetical accidents has been carried out, starting from the results calculated by Bethe-Tait model (saturated vapor pressure model).

The following assumptions were introduced to make the analysis.

1. The pressure wave is generated by the acoustic impedence effect caused by the expansion of the core.

2. Pressure drop of the pressure wave was calculated from polytropic change, assuming that the core material obeys ideal gas equation, and also from the core expansion velocity corresponding to the time when the maximum pressure is generated.

3. It is assumed that the sodium vapor pressure is generated by the heat transfer between high temperature core material and the sodium coolant. Five per cent of total energy generated during the accident is assumed to contribute blast pressure. This value was taken because it is the maximum percentage of destructive energy converted from the total released energy obtained in the past reactor experiments. (TABLE 2)

TABLE 2 Data summary of various reactivity accidents and experiments.

	SL-1	SPERT-1 Plate fuel	SPERT-1 Oxide fuel	SNAP-TRAN-2	SNAP-TRAN-3	SPERT-IV*(CDC)	TNT explosion	AWRE
Reactor period	$3.6^{ms}\pm 0.5$	3.2^{ms}	2.2^{ms}	0.2^{ms}	0.64^{ms}	4.4^{ms}, 4.7^{ms}	—	—
Inserted reactivity	~3$	3.5$	~2.6$	4.64$	3.75$	—		
Peak power	19^{GW}	2.25^{GW}	18^{GW}	74^{GW}	18^{GW}	6.5^{GW}, 5.8^{GW}	—	—
Total energy	130^{MW-s}	30.7^{MW-s}	150^{MW-s}	54^{MW-s}	45^{MW-s}	— —	—	(130^{MW-s})
Prompt energy release	$50\sim 60^{MW-s}$	—	—	54^{MW-s}	45^{MW-s}	$7,000^{cal}$, $6,700^{cal}$	—	(50^{MW-s})
Destructive energy release	$4\sim 6.1^{MW-s}$	$\sim 1^{MW-s}$	—	0.8^{MW-s}	1.8^{MW-s}	136^{cal}, 170^{cal}	—	—
Destructive energy converting ratio	~4.8%	3.3%	—	1.5%	4%	— —	—	(Same as SL-1)
Maximum pressure of pressure pulse	$7,000\sim 2,000^{psi}$	Initiai $3,000^{psi}$ Max. $8,000^{psi}$	—	$35,000^{psi}$	$1,000^{psi}$	$10,000^{psi}$	$750,000^{psi}$	$3,000^{psi}$
Vapor blast pressure (Max.)	500^{psi}	—	—	$1,000\sim 2,000^{psi}$	$200\sim 300^{psi}$	$1,500^{psi}$	—	—

* Data are test rod only.

The calculations done for JEFR under the above assumptions gave the following results.

4. About 1,000 kg/cm^2 g of pressure wave is generated about 8 millisecond after the reactor reaches prompt critical. The total energy of the pressure wave is about 8 MW-S and its pulse width (at half maximum) is about 1.5 millisecond. (Fig. 7)

5. After that, blast pressure which has slower rise time is generated. About 28 millisecond after the reactor reaches prompt critical, the pressure reaches its peak value of 28 kg/cm^{2}g. The destructive energy caused by the blast pressure is about 98 MW-S. (Fig. 7)

6. By adding together these two kinds of destructive energy, the amount of the total destructive energy generated during the hypothetical accident becomes about 106 MW-S.

TABLE 3 Comparison of destructive energy between threshold model and vapor-pressure model at JEFR maximum hypothetical accident

	Vapor-pressure model	Threshold model	Ref. 50kg TNT mock-up test
Total instructive energy	106 MW-S	160 MW-S	200 MW-S
Shock wave			
Released energy	8 MW-S	160 (120 MW-S*)	~100 MW-S
Peak pressure	1, 000 kg/cm² g	12, 000kg/cm² g Core (5, 600 kg/cm² g Na*)	75, 000 kg/cm² g
Pulse width	3. 5 ms	(1. 8 ms*)	~0. 05 ms
Peak pressure time	8 ms	(8 ms*)	~0
Sodium vapor pressure			
Released energy	98 MW-S	0	~100 MW-S
Peak pressure	21 kg/cm² g	0	~20 kg/cm³ g
Peak pressure time	36 ms or later	——	~20 ms

* Value calculated from cross expansion velocity (ref. 8–3).

The results are shown in TABLE 3 together with those obtained by the threshold model. The decrease in total destructive energy of the saturated vapor pressure model is only about 30 per cent, compared with the calculations of the threshold model. However, the difference between these two models is very large when comparison of the destructive energy is made for the pressure wave and for the blast pressure separately.

The calculated values of high explosive (TNT) to be used in the JEFR mock up experiment are shown in the third column. Except the destructive energy of the pressure wave calculated by the threshold model, all the values expected in the mock up experiment are equivalent to or larger than the calculated ones obtained in the hypothetical accident analysis.

The problems which the threshold model involves have been discussed in section 1, and the purpose of this study was to reconsider the large destructive energy of the pressure wave which was obtained by the threshold model and to separate the energy into two types realistically. Therefore, even if the energy of the pressure wave calculated from the threshold model is larger than that of the mock up test, this does not mean that the experiment carried out with TNT (powder) is not conservative.

The values indicated by * in TABLE 3 are those calculated under the assumption adopted in this report, using the results obtained by the threshold model. In this case, energy released in the from of pressure wave decreases to 120 MW-S, which is almost equal to the energy release expected in the mock up experiment.

In conclusion, considering the calculated maximum pressure and the pulse width in the hypothetical accident, the destructive force of the mock up experiment for JEFR construction with 50 kg of TNT powder will exceed the destructive energy of the hypothetical accident, although the energy of the shock wave in the mock up experiment is a little smaller than that of pressure wave obtained by the threshold model. The character of the blast pressure of high temperature gas in the mock up experiment is similar to that of sodium vapor. Therefore, in all respects, the mock up experiment with 50 kg of TNT is considered to be reasonable as the proof test for the containment structure of JEFR.

6. Discussion

A study of the destructive energy release at the hypothetical accident of JEFR is performed in this report. The main purpose of this study was to find some correspondence between an analytical work and the reactor vessel integrity test with high explosive for JEFR. The analytical works were performed on the calculation results of the AX-1 code. The integrity tests were performed with TNT powder explosion. Both results well corresponded and were in reasonable agreement.

Here, authors wish to discuss in detail the problems which are realized to be critical through this study.

The first one is that current assumptions of the hypothetical accident are extremely conservative. For example, melted fuel is assumed to flow down with gravitation. It takes about 150 ms that the melted fuel at the core center reaches to the core bottom with gravitation. But on the contrary, core disintegration occurs only 8 ms after prompt criticality is attained. The gravitational fuel drop in vaccum spase is assumed to earn effective amount of reactivity insertion rate[5], say 40~50 S/sec[32], at the time when prompt criticality is reached. During this period, coolant is kept out of the core region. If a little amount of coolant exists in the core or a coolant vapor exists in the core, results would be very much different. If there were a little amount of coolant in the core, it would take some heat from melted core and thus pressure wave and blast pressure would become smaller as demonstrated in the SPERT and the TREAT experiments. The accidental phenomena in this case would be equivalent to the past reactor destructive test results.

If there were some coolant vapor in the core, it would make the melted core expand much rapidly[5),32], and thus, total excursion energy would be much smaller, just as we have already discussed in the section 1 about the differences between the threshold model and the saturated vapor model.

The above discussion shows that extremely conservative assumption can easily yield excess conservative analytical conclusions on the hypothetical accident. Authors feel that current assumptions on the hypothetical accident, such as the threshold model, perfect coolant ejection and so on, are extremely conservative.

The study performed under the newly developed method yielded relatively realistic results, though, authros still feel that this results are conservative too, since the calculation starts from the current conservative assumption, and that the study would be more realistic if a hypothetical accident assumptions become more realistic.

Once realistic hypothetical accident assumptions are established, both the pressure wave and blast pressure would be generated.

Damages with the pressure wave are generally determined with its amount of energy and peak pressure. Since pressure wave is propagated through media, the peak pressure of the pressure wave should be the maximum pressure of the media and not the pressure of the melted core. Therefore, the melted core expansion calculation should include interaction between surrounding materials. The calculations in this report are not accurate since this interaction is ignored (Ref. 3. 1). However, even in this calculation, 5,600 kg/cm^2 of peak pressure of the pressure wave is compared with 12,000 kg/cm^2 of maximum melted core pressure in **Fig. 3a**. Namely, the calculated peak pressure decreases to about one half of the maximum melted core pressure. If more detailed calculation were performed, it would be much smaller, since the expansion speed would decrease with the coolant resistance.

Blast pressure would be generated with heat transfer, since it is caused with steam expansion. Five per cent of maximum energy convertion ratio is used in the calculation[20]. However, smaller ratio might be better for liquid metals, since they have better heat conductivity which transfers more heat to neighbour resulting in less void formation.

When heat transfer is considered, we have to discuss another 95 per cent of excursion energy which is used for increasing the temperature of coolent and other materials in the system. It is considered that some amount of this energy would be released later, but other majority would be released simultaneonsly at the time of the accident. It means that majority of 95 per cent of excursion energy is released simultaneonsly but it is not convert to destructive enery. In other word, heat transfer starts at the beginning of the accident, therefore, isothermal core expansion becomes conservative assumption. Thus, the pressure wave is expected to decrease quicker and the energy of the pressure wave would be smaller.

As explained in the above discussion, the calculations performed in this report are conservative in respect of energy, even though they show relatively realistic results. If it were, hypothetical accient would become less severe and would be equivalent to usual reactivity accident, since more than several hundred atms of peak pressure of the pressure wave and significant energy release arose in past reactivity accidents. Again, if it were, is there any reason to survive such a complex and unrealistic hypothetical accident assumption that make the reactor super prompt critical with melted fuel?

Finally, a model to calculate destructive energy release of the fast reactor hypothetical accident has been developed. Several other models were examined before completion of this model; however, all of these do not to give satisfactory answer.

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