Containability of Effect of Molten Fuel Release in Fast Reactor Fuel-Subassembly

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Received August 19, 1974

This paper discusses various alternative safety implications relevant to local faults in LMFBR, and evaluates the basic factors affecting the ability of the subassembly wrapper wall to contain the various effects of molten fuel release. The response of the wrapper tube is evaluated by the method proposed by Youngdahl. Firstly, an equation is derived for calculating the energy repartition between the portions consumed in wall deformation and sodium slug acceleration. Then, using this equation, analyses are performed covering various situations where molten fuel coolant interaction (FCI) significantly affects the surrounding matter. This analysis shows that the degree of coherence in fuel mixing process alters substantially the severity of the FCI. The peak pressure generated by the FCI depends on the volume of the mixing zone, which is closely related to the spatial randomness of fuel failure: For the case of a MONJU-type core design, if the height of the mixing zone is greater than 2 cm, the effects of the release of 200 g of molten fuel can be contained within the subassembly without damaging the unaffected wrapper tube. Melt-through of the wrapper tube is also analyzed, and it is found that the integrity of the adjacent wrapper tube is lost about 16 sec after deposition of the molten fuel, and that the melt-through process would differ substantially according to whether forced convection is present or absent in the subassembly gap.

KEYWORDS: LMFBR type reactors, reactor safety, local fault, wrapper tubes, subassembly, fuel coolant interaction, molten fuel release, MONJU

I. INTRODUCTION

It has been pointed out that local core faults in liquid-metal-cooled fast-breeder reactors (LMFBR) might occur without generating signals detectable by core instrumentation. If any local faults cause fuel failure and release of molten fuel, fuel/coolant interaction (FCI) will occur. The two general types of fault of interest in potential fuel failure and release of molten fuel are: (1) cooling disturbance due to large-scale subassembly blockage, (2) fuel-subassembly loading error. The FCI following the release of molten fuel may cause failure of the adjacent subassembly wrapper walls. These failures may, if severe, damage the rest of the core or the control system, and this would have serious consequences. Much effort has been directed in the past to experimental and analytical studies aimed at clarifying the characteristics of this type of faults\(^\text{(1)-(4)}\). The problem is complicated by the fact that a too strong wrapper tube would, obviously, impair the core performance. It thus becomes important not only to evaluate the effect of the FCI in the subassembly but also to establish safety design criteria for this type of fault. These two approaches should be indispensable for industrial subassembly design work. The purpose of the present paper is to discuss various alternative safety implications relevant to such local faults, and to evaluate the ability of subassembly wrapper tubes to contain the

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various effects of molten-fuel release. In Chap. II, the safety implications of local faults in the LMFBR are briefly dealt with, and various situations associated with molten-fuel release are discussed and summarized. In Chap. III, three typical situations where molten fuel plays a major role in damaging the surrounding structure are analyzed and discussed. In view of the various uncertainties inherent in any analysis, the critical features characterizing each situation are specified in particular.

II. SIGNIFICANCE OF LOCAL FAULTS

1. Fault Categorization

In the safety design of nuclear reactors, the following categories are commonly used to classify faults, based on the expected hazards they present and on the probability of their occurrence(5).

(1) Safe Fault
Fault that falls into the category where: no damage to the reactor is expected to ensue.

(2) Minor Fault
Fault that falls into the category where:

1) minor damage to the reactor such as fuel rupture and fuel bowing is expected to ensue, and
2) the estimated probability of occurrence would be around once per a few years.

(3) Major Fault
Fault that falls into the category where:

1) major damage to the reactor such as the fuel failure and the release of molten fuel is expected to ensue, and
2) the estimated probability of occurrence would be between once during several reactor lives and once in \(10^8\) yr.

(4) Catastrophic Fault
Fault that falls into the category where:

1) catastrophic damage to the reactor such as core destruction is expected to ensue, and
2) the estimated probability of occurrence would be around once in \(10^4\) yr.

(5) Negligible Fault
Fault that falls into the category where: the probability of occurrence is below once in \(10^8\) yr.

The severity of the consequences resulting from the local faults mentioned in Introduction is expected to be equal or greater than that of a major fault, as defined above. As for the probability of their occurrence, it is expected to be quite small, on account of the numerous measures devised to reduce the chances of their occurrence and/or to remove the causes thereof. With particular reference to local flow blockage, the inlet nozzle of the subassembly is today usually designed so as to preclude the Fermi-type blockage(6), and present day safety design criteria prohibit the designer from using lubricants made of hydrocarbon in the primary coolant circuit so as to prevent sub-channel blockage such as experienced in the SRE reactor(7). The possibility of occurrence of fuel loading error is usually eliminated by high-level quality control during fuel fabrication, and by adequate check procedures established for refueling operation. Experience accumulated to date on this type of reactor, however, is too scarce to provide any assurance on the validity of the estimated frequency of once in \(10^4\) yr. We must, under these circumstances, adopt the more conservative assumption that the probability of occurrence of such a fault is about once during a few reactor lives. This makes it necessary to show that the consequences of such a fault are far less serious than the case of a catastrophic fault.

A fault tree for the combination of untoward events affecting subassemblies leading to catastrophic failure is depicted in Fig. 1. Analysis of this fault tree points toward a number of different measures to prevent such occurrence. Among them are measures to block the critical path to the disastrous final issue, which include:

1) Equipping each subassembly with detectors capable of perceiving faults in their early stages and scrambling the reactor prior to the development of more serious consequences.

2) Installing local detectors capable of perceiving FCI phenomena ensuing from
the above-mentioned faults, under the assumption that the damage caused by these interactions are mild enough not to cause rapid failure propagation and not to deteriorate the scram system.

(3) Proving, both analytically and experimentally, that these faults cannot cause any catastrophic results such as failure propagation between subassemblies. Thus, if it is difficult to show that the probable frequency of these local faults is less than or equal to once in $10^6$ yr, one or more of the measures enumerated above should have to be taken up for assuring the safety of LMFBR.

For applying the first method, it is necessary to confirm the capability and reliability of the detection system. While, for this purpose, much effort has been devoted to the development of both sensors and to sensor systems$^{[9][10]}$, the results obtained so far are not adequate to permit dependence solely on this means for meeting the above requirement. The second approach is more promising than the first, because the expected symptoms of FCI phenomena would be more easily detected than those of the initiating events. It is necessary in this case, however, to prove the validity of the assumption on which this approach is based, i.e., that the damage incurred before the safety mechanism is brought into effect is tolerably small. The third method depends solely on the physical nature of the core structure, and is a passive approach. If this approach can gain its objective without deteriorating the core performance beyond endurance, it can be considered to be the most promising approach. In this case the first and the second approaches can be pursued in parallel, and with the burden of reliance applying on the local instrumentation system lightened substantially, since the primary objective of these detectors would no longer be to scram the reactor but to pin-point the location of the faults when an anomalous signal is detected.

2. Description of Typical Situations

Based on the above preliminary consideration, the extent of quantitative analysis requiring to be performed can be assessed. Since the most practical approach is the third, the most important work would be to
show the limit of capability of the core structure to contain the effects of FCI caused by the local faults.

It is already established that violent interaction between molten fuel and coolant is the most important among the possible sources of pressure in a single subassembly. But analytical method developed so far to deal with the thermo-hydrodynamics in subassemblies have not yet made it possible to predict with adequate precision and reliability the transient behavior of fuel pins, coolant and molten fuel. A rough description thereof, however, can be obtained with use made of a single-pin single-channel transient analysis code such as FORE-Ⅱ and SAS-2A.

It has been made clear that a large number of coolant subchannels or a large fraction of the inlet nozzles should be blocked before the fuel would fail. In the event of such a severe coolant blockage, fuel melting and molten fuel ejection is likely to occur after coolant voiding. However it is difficult to estimate the amount of molten fuel which would be released from the pin and become mixed with the residual sodium in the voided subassembly. We shall therefore conservatively assume that the fuel pin collapses when 30% of its cross section has melted and that upon collapse, all of the molten fuel runs down simultaneously by gravitational force. At this juncture, the maximum possible amount of molten fuel which can be mixed with the residual sodium before large pressure due to FCI is generated is calculated to be 1 kg or so. On the other hand, if violent reaction does not occur, the molten fuel would collect in the lower part of the subassembly. In this case the coolant sodium will strike the surface of the molten fuel pool upon reentry of the coolant. While it is difficult to predict the mode of reentry and the thickness of the mixing zone for this case, it is here assumed to be 1 cm. Then the amount of molten fuel participating in the FCI is estimated to be about 400 g. This is only a tentative value and should be studied further.

In the event of a loading error of a subassembly, in which a charge containing excessively high fissile density fuel is loaded into the central core zone, a part of the fuel pin melts steadily. The total inventory of the molten fuel produced in this case is estimated from calculation to be 10 kg. It has been shown from in-pile experiments that even if fuel melts transiently, molten fuel is likely to move axially through the central column of the fuel and they are not likely to be released into the coolant channel. It is predicted also that these fuel pins will hold without failing for a considerable period. It is, however, not unreasonable to assume that molten fuel could actually be released into the coolant channel, because it is quite possible that these mis-loaded fuels would acquire local cladding defects toward the end of their lives. In this case, the amount of molten fuel which could be released before the pressure of the coolant channel builds up due to FCI is calculated to be 50 g or so, which is consistent with the results of analysis given in Ref. (15). After the pressure surge due to FCI ends and the channel is voided, about 4 kg of molten fuel are released, which would run down to the bottom in a second or so. This situation is similar to the case of inlet flow blockage. However it is difficult to estimate the maximum amount of molten fuel which can mix with the sodium before the next FCI. Presumably it is less than 1 kg because after the molten fuel runs down and comes into contact with the sodium, only a short time is available before the generation of the next pressure pulse.

In the case of a local subchannel blockage, significant amounts of fuel melting cannot be expected without postulating unreasonable assumptions such as complete loss of heat transfer at blockage and/or more than 50% blockage of the coolant channel. Estimates of the amount of fuel released vary with the extent of blocked area, and range from a few grams to 200 g or so.

The result of the above survey is sum-
marized in Table 1. In the last column of this table, the condition of the coolant channel is specified. It is important to specify whether the channel is voided or not, because the expected work potential of FCI is reduced significantly if large space is available for the fuel sodium mixture to expand. It is seen from this table that, for assessing the capability of the subassembly wrapper to prevent local faults from further propagation, an analysis should be made of the following three typical situations.

<table>
<thead>
<tr>
<th>Type of fault</th>
<th>Inventory of molten fuel</th>
<th>Type of release</th>
<th>Amount of molten fuel mixed with sodium</th>
<th>State of coolant in subassembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet blockage</td>
<td>~10 kg</td>
<td>Drip-down</td>
<td>~1 kg</td>
<td>Voiding</td>
</tr>
<tr>
<td>Loading error</td>
<td>~10 kg</td>
<td>Stored as pool of fuel</td>
<td>~400 g</td>
<td>Reentry</td>
</tr>
<tr>
<td>Local blockage</td>
<td>~200 g</td>
<td>Ejection</td>
<td>50 g</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Drip-down</td>
<td>&lt;1 kg</td>
<td>Voiding</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~200 g</td>
<td>Local voiding</td>
</tr>
</tbody>
</table>

(A) 50 to 200 g of molten fuel is ejected into the coolant sodium.
(B) 1 kg of molten fuel interacts with sodium under the surface of the sodium pool.
(C) Molten fuel deposits on the subassembly wrapper wall.

These three situations are depicted schematically in Fig. 2. The severity and its critical features are analyzed and discussed in the next chapter.

III. TRANSIENT INTEGRITY OF AWRAPPER

In this chapter, the possibilities of loss of integrity of a wrapper are studied for the three situations prescribed in the preceding chapter. Before analyzing each situation, a method for evaluating the effects of FCI is described.

1. Repartition of Mechanical Work Energy from FCI

The pressure pulse generated by the FCI process causes both deformation of subassembly wrapper tube and ejection of coolant sodium above the interaction zone. Several calculations have been published on the deformation of the tube wall under given pressure loadings, undertaken in studies to evaluate the damage potential of the FCI process\(^{15} \sim 20\). It is clear that the pressure behavior is sensitive by dependent on both deformation and displacement of the surrounding matter, and hence the repartition between these two processes of the mechanical work energy liberated by the FCI process becomes an important question.

The displacement \( U \) undergone by the
center of one side of the hexagon can be
calculated on the basis of Youngdahl's ap-
proach to the dynamic plastic deformation
of structure (outline given in Appendix).
If the pressure-time relation is assumed to be
\[ P(t) = P_0 e^{-\beta t}, \]
then
\[ U = \frac{a I_{\infty}}{P_0} F(P_y/P_0), \]
where \( a \) is a constant which is found to be
0.72, \( \rho \) the density of the tube material, \( B \)
the thickness of the tube, and \( P_y \) the yield
stress of the hexagon calculated by Eq. (A6)
in Appendix.

The total impulse of the pressure loading,
\( I_m \), is defined by
\[ I_m = \int_0^\infty P(t) dt, \]
where an appropriate final pressure should
be chosen for a given condition of accident.
The effectiveness of the pressure loading \( F \)
is calculated numerically, using the relation
described in Appendix and depicted in Fig.
3 as a function of \( P_y/P_0 \). It should be
noted that \( F \) is zero if \( P_y \) exceeds \( P_0 \), and
0.5 if it is equal to 0.3\( P_0 \).

The energy absorbed by the hexagonal
tube \( E_d \) is calculated approximately by the
relation
\[ E_d = 6P_y L U H_d, \]
when the rigid/perfectly-plastic relation is
assumed for the stress-strain relationship
applicable to the tube material.

The kinetic energy removed by the sodium
column in the subassembly \( E_k \) is evaluated
easily from the equation of motion of the
column, mass of which is \( M_f \):
\[ M_f \frac{dv}{dt} = AP(t) - M_f g, \quad i = su, sl \]
This equation gives
\[ E_k = \left( \frac{1}{2M_{su}} + \frac{1}{2M_{sl}} \right) A^2 P_0^2. \]

The sum of \( E_d \) and \( E_k \) is the energy of
the mechanical work done by the pressure
loading \( I_m \), and should be equal to \( E_t \) the
mechanical energy liberated:
\[ E_d + E_k = E_i = \eta M_f E_f, \]
where \( M_f \) is the mass of molten fuel in-
volved in the process of FCI, \( E_f \) the internal
energy of the molten fuel, and \( \eta \) the effi-
ciency of the FCI process to convert thermal
energy of molten fuel into mechanical work.
From Eq. (7), the fraction of \( E_t \) used for
straining the tube wall is
\[ \frac{E_d}{E_t} = \left[ 1 + \frac{A^2}{2} \left( \frac{1}{M_{su}} + \frac{1}{M_{sl}} \right) \right] \]
\[ \frac{6LH_d}{\left( \rho B \right)_{eff} F(P_y/P_0)} \]^{-1}. (8)
From this equation, if \( \eta \) is assumed to be
independent of the circumstances in which
the FCI takes place, the relation between \( U \)
and the geometry of the subassembly be-
comes
\[ U = \eta \frac{E_f M_f}{6P_y L H_d} \left[ 1 + \frac{A^2}{2} \left( \frac{1}{M_{su}} + \frac{1}{M_{sl}} \right) \right] \]
\[ \frac{6LH_d}{\left( \rho B \right)_{eff} F(P_y/P_0)} \]^{-1}. (9)
Calculations have been carried out using
Eqs. (8) and (9) to determine the conse-
quences of molten fuel release in the sub-
assembly of LMFBR. The values adopted
for the various parameters are based on the
design value of MONJU (Japanese prototype
LMFBR). The half width of one side of a
wrapper (\( L \)) is 32 mm, and its thickness (\( B \))
3 mm. The effective mass of a wrapper
(\( \rho B \)_{eff} is assumed to be 2\( \rho B \), since the wall
of the adjacent wrapper is expected to de-
form in a mode associated with that of the
affected wrapper. In Fig. 4, \( E_d/E_t \) is de-
picted as function of \( P_y/P_0 \) for various

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\[ \text{Fig. 3 Effectiveness of pressure pulse } F(P_y/P_0) \text{ as function of } P_y/P_0 \] (ratio between yield pressure and peak pressure)
values of $M_{su}$. If $P_y/P_o$ is greater than 1, $F$ becomes zero, and then $E_t$ comprises solely the kinetic energy of the sodium column. If $P_o$ is 2$P_y$, about 90% of $E_t$ transforms into energy of deformation applied to the tube wall. Even in such a case, if the upper part of the subassembly is voided and $M_{su}$ is reduced to 1/20 of the reference value, then this fraction is reduced to about 40%. What is notable here is that, if a subassembly is completely filled with coolant sodium, most of the liberated energy would be spent in straining the wrapper when the peak value of the pressure loading $P_o$ exceeds twice the yield pressure of the wrapper $P_y$.

![Fraction of pressure pulse energy used to deform subassembly, for various values of $M_{su}$](Image)

To discuss the relation between the deformation of the wall and the mechanical work energy $E_t$, using Eqs. (8) and (9), it is necessary to evaluate $\eta$, $P_y$ and $P_o$. Much effort has been directed toward obtaining a better understanding of the FCI process ever since Hicks & Menzies(22) pointed out the significance of the mechanical work energy produced by the interaction of molten fuel with sodium and proposed a method for its calculating. Yet it still remains to establish a precise method of predicting the value of $\eta$, the controlling mechanism still being unclarified quantitatively. A series of tests using the TREAT reactor performed at the Argonne National Laboratory has specifically examined this mechanism(23). The results, which on a small scale are at least characteristic of the failure modes expected in a large reactor, lead one to conclude that the efficiency seen in the conversion of the heat of the molten fuel into destructive work is far below 1%(24). Based on this fact, a reference value of 1% is adopted for $\eta$, and in a limited number of cases, calculations are made with $\eta=0.1\%$ for purposes of comparison.

It is also difficult to determine $P_y$. A subassembly which is irradiated to 10% burn-up receives a total neutron fluence of about $3\times10^{22}$ n/cm². This irradiation increases the yield stress and decreases the ductility of the steel as compared with the unirradiated material. Such changes in the properties of steel have been measured, but data are incomplete. Based on available information(26), it was decided to adopt for 316SS the values of yield stress $\sigma_y=70$ kg/mm² and failure strain $\varepsilon_f=0.03$ at 500°C and 20 kg/mm² at 700°C.

The peak pressure $P_o$ depends sensitively upon the geometry and the gas content of the fuel coolant mixture. The latest model available for FCI analysis, originally derived by Cho & Wright(26), gives two types of pressure peak, the first generated under acoustic restraint (acoustic peak) and the second peak, caused by the rapid vaporization of sodium (vaporization peak). The acoustic peak is attenuated rapidly in the presence of vapor in the mixture or in the neighborhood thereof(23). In the case of fuel pin failure due to overpower(27), the molten fuel is probably ejected into the sodium by the action of the fission product gas. It may hence be assumed that the contribution of this part of the pressure spike becomes negligible. The height of the vaporization peak is limited below the saturation pressure of the mixture, that is

$$P_o \leq P_{sat}(T_m),$$

where $T_m$ is the temperature of the mixture. Thus, it should be noted that the severity of the FCI process depends strongly on the volume of the mixing zone. Based on the
above mentioned model and data, the consequences of two situations (A) and (B) given below are analyzed:

(A) FCI due to molten fuel ejection into coolant sodium

The first situation assumes that molten fuel is ejected into the coolant sodium after fuel failure due to a transient overpower fault. If it is assumed that 200 fuel pins fail simultaneously at the same axial location, the height of the mixing zone $H_m$ would be about 1 cm. We adopt this value as standard reference figure, and some cases where $H_m = 2$ cm are also calculated in order to determine the effect of spatially random failure location. This value also can be considered amply conservative, since fairly large scattering of failure location has been reported from out of pile simulation studies.(28)

Table 2 summarizes the deformation $U$ of the wall and the peak pressure $P_0$ calculated using various values of $M_f$, $H_m$ and $\eta$. If $\eta$ is equal to 1%, $U$ becomes quite large when $P_0$ slightly exceeds $P_0$ and the ejection of only 80 g of molten fuel constitutes the limit of containment without damage to the wrapper tube. If $\eta$ is reduced to 0.1% the ejection of 100 g molten fuel causes 3% strain of tube wall, and $U$ becomes relatively insensitive to the amount of molten fuel ejected. The other important point is that scattering of fuel pin failure location should cause a significant reduction in the damaging capability of the FCI process, as shown in Table 2 for the case where $H_m$ is doubled. In this last case, about 150 g of molten fuel can be ejected without damaging the tube wall even if $\eta$ is 1%.

These results indicate that, if the ejection of 200 g of molten fuel is to be accommodated without damaging the adjacent wrapper tube, it is necessary to prove that the efficiency $\eta$ is smaller than 1%, and that the axial locations of the fuel pin failures are distributed in an axial zone broader than 2 cm. If this condition cannot be fulfilled, we are obliged either to abandon the third approach defined in Sec. II-1 or else to increase the strength of the wrapper tube.

(B) FCI process under the surface of sodium pool in a subassembly

In the case of fuel melt occurring with local loss of flow, it is expected that more than 4 kg of molten fuel fall onto the surface of the sodium pool formed in the lower part of a fuel subassembly, as schematically shown in Fig. 2. Only limited observations have so far been obtained on the collapsing behavior of molten fuel pins, whether in out-of-pile(28) or in in-pile experiments(29). But the results agree in their indication that no large quantity of molten fuel would fall in a lump, and that instead, there would occur sporadic dripping of relatively small drops. If, then, it is permissible to assume similar sporadic dripping in the far larger fuel subassemblies compared with the experimental set-ups, it is expected that the fraction of the total heat energy that would be converted into mechanical energy and applied to deform the tube wall should become quite small. This expectation is supported by the following observations.

(1) Because the molten fuel mixes with only a limited amount of the sodium in the coolant channels of the subassembly, $M_{su}$ is far smaller than in the case of fuel ejection into the coolant. This reduces the ratio $E_{a}/E_{s}$, as can be seen in Fig. 4.

(2) Because the mixing zone is located near the free surface of the residual sodium in the subassembly, the duration
of acoustic restraint is quite small, and most of the heat energy of fuel is delivered to the sodium by two-phase heat transfer, which is considered to be a process that is less efficient than that of single-phase heat transfer. Consequently, the heat energy of fuel diffuses into the bulk of the sodium rather than concentrate in some part of the sodium near the fuel. This would tend to attenuate the rise of mixing temperature $T_m$, which, in turn would make it improbable that the peak pressure $P_o$ would rise any further than in case (A), and $E_d/E_t$ can be expected to be small.

(3) Because the heat energy of the fuel diffuses into the bulk of the remaining sodium, the efficiency $\eta$ for converting the heat energy into mechanical work energy would become small.

Of course, there remains some possibility for the falling molten fuel to remain in a single mass deep in the sodium pool, instead of instantly undergoing fragmentation, to remain thus lumped together for a while, and then abruptly disintegrate, which could trigger a vapor explosion under certain conditions\(^{(29)}\). Thus, the validity of the three premises set forth above must be confirmed by realistic experiments. The results of recent out-of-pile FCI experiments at ANL\(^{(31)}\) would appear to support these premises.

If the basic assumption of sporadic dripping comes to be disproved, consequences substantially more severe should have been expected. In this case it becomes necessary to analyze a situation in which 4 kg of molten fuel fall on the surface of the sodium pool, of which 1 kg is mixed with the sodium within a few milliseconds. Here the value of $M_{su}$ is about 4 kg, and the width of the mixing zone $H_m$ may be 2~8 cm\(^{(31)}\). The coolant subchannel is too narrow to allow the molten fuel to mix with a large volume of sodium within such a short interval. It would thus be difficult to maintain that the axial height of mixing zone should be any greater than 8 cm.

The results of the calculation of $U$ are presented in Table 3. It is indicated from this that even if $\eta$ is 0.1% the tube wall would fail when the axial height of the mixing zone is smaller than 8 cm, and that, under the assumption of lumped dropping of fuel, we are obliged to abandon the third approach defined in Sec. II-1, since it is impractical to envisage a wrapper wall such as would withstand such a high pressure pulse.

\[
\begin{array}{ccc}
H_m (\text{cm}) & P_o (\text{kg/cm}^2) & U (\text{cm}) \\
2 & 630 & 13.1 \\
4 & 260 & 13.0 \\
6 & 110 & 11.5 \\
8 & 70 & 0 \\
\end{array}
\]

2. Molten Fuel Pool in Subassembly

In the case of massive fuel meltdown in a subassembly, there remains the possibility of a breach affecting the wrapper tube caused by melt-through due to contact with the molten fuel, even if the fuel has not initiated the FCI process. Several studies\(^{(15)(16)(31)-(33)}\) have dealt with the analysis of this type of transient. These studies have utilized transient heat conduction codes and have evaluated the possibility of melt-through, and in the case of such occurrence, the time required for this event.

The present author also developed the code SARUP\(^{(24)}\) for evaluating this phenomena, postulating the geometry shown in Fig. 5 and assuming that: (1) the sodium in the intrasubassembly gap is subjected to the condition of forced convection, (2) vapor blanketing occurs in the intrasubassembly gap immediately following the onset of sodium boiling, (3) the molten steel of the wrapper tube drains off at the steel/fuel interface. (A note on this code will be published in a separate paper.) In this situation of molten-fuel pool in a subassembly, our main interest lies in the possibility of failure.
propagation. For this reason, we have calculated the melt-through time for the wrapper tube using this code and assuming the geometry given in Fig. 5.

![Diagram of melt-through calculations]

The results are presented in Table 4. The wrapper-tube melt-through time is found to be 6 sec when the intrasubassembly sodium is stagnant, and this time is increased to 10 sec when the sodium flows at the design velocity of 23.5 cm/sec. The integrity of the adjacent wrapper tube wall is lost upon lapse of 17 to 20 sec after the deposition of molten fuel on the relevant wrapper tube. This result indicates that the melt-through process could be substantially modified if sufficient forced convection in the intrasubassembly is assured under accidental conditions. It is also shown that sodium boiling begins in the affected subassembly after 20 or 23 sec.

The above analysis of boiling propagation requires further examination, on account of the assumption adopted in the SARUP code of drainage of molten steel at the fuel/steel interface, and neglect of the mixing process taking place in the unaffected subassembly.

It is clear that if complete mixing is assumed to exist in the unaffected subassembly, coolant boiling would be prevented by the large heat capacity of the coolant in the subassembly. As for the effect of drainage, another calculation provides assurance that its absence should tend to delay the melt-through to some extent. For the time being, however, it would appear appropriate to base calculations on the assumption of complete drainage of molten steel, since experimental data are still insufficient to justify the renunciation of this conservative assumption. This result suggests that it is difficult to rely solely on the third approach defined in Sec. II-1, since the affected wrapper would inevitably be ruptured if deposition of the molten fuel is assumed with the present geometry and parameters.

### IV. CONCLUSION

The work reported here leads to the following conclusions.

While various means have been devised for reducing the probability of occurrence of local faults that would involve fuel melting, it still remains to establish dependable evidence that the consequences of such local faults are far less serious than in the case of catastrophic faults.

The most important and practical measure to be adopted today is still to confine the various effects of these local faults within the affected subassembly and to block the critical path for these local faults to propagate over the whole core.

The mechanical work energy generated...
by the FCI process is consumed both in accelerating the upper and lower sodium columns and in deforming the subassembly wrapper wall. The repartition of the energy between these two processes depends on $P_y/P_0$, $M_{su}$ and $\eta$.

The deformation of the wall caused by the FCI depends particularly strongly on $P_y/P_0$ and $\eta$. The peak pressure $P_0$ generated by the FCI depends on the volume of the mixing zone, which is closely related to the spatial lumping of fuel failure. For the case of MONJU type core arrangement, the effect of the release of 200 g of molten fuel can be contained within the subassembly without damaging other unaffected wrapper tubes, if the height of mixing zone is greater than 2 cm.

Even in the case of massive fuel collapse subsequent to voiding of the subassembly, the effect of the resulting FCI can be contained within the affected subassembly, if the molten fuel drips sporadically into the remaining sodium.

In a case in which the molten fuel remains in the lower part of the subassembly, the integrity of the adjacent wrapper tube is lost about 16 sec after deposition of the molten fuel. In this situation the existence of forced convection in the intrasubassembly gap attenuates the melt-through process substantially.

It is problematic to rely only on the third approach defined in Sec. II-1, because there remains the possibility of wrapper tube failure caused by the melt-through process and the generation of inordinately large pressure loadings due to lumped fuel failure and mixing.

Uncertainties inevitably accompany any evaluation, subjected as they are to limitations in the amount of available experimental data. None the less, it can be expected that the extent of the uncertainty would be reduced significantly if the efficiency $\eta$ of FCI and the sporadic nature of fuel failure can be predicted with better reliability and the pattern of fuel motion clarified.

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**[NOMENCLATURE]**

$A$: Cross section of flow area in subassembly  
$a$: Constant (=0.72)  
$B$: Thickness of subassembly wrapper  
$E$: Energy, $e$: Strain  
$F$: Effectiveness function  
$g$: Gravity constant  
$H$: Axial height  
$I$: Pressure impulse  
$L$: Half-width of one side of hexagonal wrapper  
$M$: Mass, $P$: Pressure, $t$: Time  
$U$: Displacement of side of wrapper  
$v$: Velocity  
$\beta$: Decay constant of pressure  
$\gamma$: Efficiency of FCI  
$\rho$: Density, $\sigma$: Stress

Subscripts  
$d$: Deformation, eff: Effective  
$f$: Fuel, $k$: Kinetic  
$m$: Mixture, $0$: Peak  
$sat$: Saturation  
$sl$: Lower sodium column  
$su$: Upper sodium column  
$t$: Total, $y$: Yield

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**REFERENCES**


Youngdahl has derived many expressions for the dynamic plastic deformation of structures. Its application to the response of a hexagonal tube to an internal pressure pulse is described briefly by Youngdahl & Rosenberg. A simple rheological model has to be used. If it is applied to a static case, a limiting load or yield pressure $P_y$ is obtained. If the internal pressure is smaller than $P_y$, there is no deformation; and if it exceeds $P_y$, deformation continues indefinitely. The purpose of this analysis is to predict the effect of pressure exceeding $P_y$ applied for a short time.

The calculations mentioned in Ref. (21) show that if $U$ is the displacement of the center of one side of the hexagon, then for $U < B$,

$$ U \approx \frac{aI^2}{\rho_s B P_e} \left( 1 - \frac{P}{P_e} \right) \quad (A1) $$

Here $P_e$ is the effective pressure and $I$ the pressure impulse (defined below), $\rho_s$ the density of the material, $B$ the thickness of the wall and $a$ a constant. If $P(t)$ is the pressure difference between the tube interior and exterior, then $I$ is defined by

$$ I = \int_{t_y}^{t_f} P(t) dt \quad (A2) $$

where $t_y$ is the time at which motion starts (i.e., when $P$ first exceeds $P_y$), and $t_f$ the time when it stops. The value of $t_f$ is found from

$$ P_y(t_f - t_y) = \int_{t_y}^{t_f} P(t) dt = I. \quad (A3) $$

The effective pressure $P_e$ is defined by

$$ P_e = I/2t_m \quad (A4) $$

where $t_m$ is the "centroid" of the pulse, given by

$$ It_m = \int_{t_y}^{t_f} (t - t_y) P(t) dt. \quad (A5) $$

The yield pressure is given by

$$ P_y = 8a_s \alpha^2 / (1 + \sqrt{(1 + 4\alpha^2)}), \quad (A6) $$

where $\alpha = B/2L$.

Equations (A1)~(A6) can be evaluated if the variation of $P$ with $t$ is known. The result expressed in Eq. (2) and Fig. 3 are for the exponential pulses given by Eq. (1).