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ANALYSIS OF THE
FFTF PRIMARY-SYSTEM RESPONSE
TO AN HCDA

by

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Reactor Analysis and Safety Division

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ANALYSIS OF THE FFTF PRIMARY-SYSTEM RESPONSE TO AN HCDA

by

Y. W. Chang and J. Gvildys

ABSTRACT

This report describes the analysis of the FFTF primary-system response to a hypothetical core-disruptive accident of 150 MW-sec using the REXCO-HEP computer code. REXCO-HEP is the latest version of the REXCO code that treats not only the hydrodynamics, but also the elastic and plastic deformation of the reactor structures and components. The mathematical model of the FFTF reactor is described in detail, particularly in the areas of modeling of reactor internals and extending the time range for which reliable calculation can be made. The basic assumptions and limitations of the model are also discussed.

I. INTRODUCTION

Although large liquid-metal fast breeder reactors (LMFBR) can be designed for safe and reliable operation so that the occurrence of a whole-core meltdown accident has an extremely low probability, the safety assessment of the reactor design requires an analysis of the capability of the primary containment system to sustain the consequences of such an accident, even though it is a hypothetical one. It is desirable that the primary containment should not be breached throughout the event, the decay heat be continuously removed from the damaged core without causing a meltthrough of the primary containment, and the fission products and other radioactive materials should not be released to the surroundings.

To accomplish this objective, the reactor designer must know the amount of energy released in such an accident and the energy available for performing work on the system. A major part of the fast-reactor safety work in the U.S. has been concerned with estimates of these energies. Development of methods and calculations of this nature have been in progress for several years. However, the final objective of most accident analyses is to determine what effect the excursion will ultimately have on the primary containment; therefore, the reactor designer must also know the dynamic response of the reactor system to accident loads.

The determination of the dynamic response of the primary system to a hypothetical nuclear excursion is a complex problem. It involves not only the calculation of the response of containment structures, but also the propagation of pressure waves, the interactions of fluid and structures,

the loads imposed on components and structures adjacent to the core, and the damage produced by these loads. The reactor designer must also know the sequence of failure of the various components, since early failure of one component may change the loadings on other parts of the system.

Because of the complexity of the problem, the early approach was to perform model experiments¹⁻³ in which the hypothetical core disruptive accident (HCDA) was simulated by the use of high explosives and the sodium was replaced by water. However, the characteristics of the energy release in nuclear excursions and explosions are quite different. In a nuclear excursion, most of the energy released will be mainly determined by the expanding core; for high explosives, half of the energy is in the shock wave which compresses the media and performs work on the system immediately after detonation. Therefore, to perform a useful test, not only must the reactor-containment structure and internals be properly represented by a scaled model, but also the rate of energy release from the core must be properly simulated by the chemical explosives. If the reactor-system configurations and/or the magnitude and duration on energy release do not fall within the spectrum that has been studied experimentally, judicious estimates must be made in applying the results of the experiments.

A different approach to the problem is to use the basic conservation equations of mass, momentum, and energy, together with the equations of state of the reactor materials, and calculate the response of containment structure under postulated nuclear-excursion conditions. In recent years, the development of high-speed computers has made it feasible to use computer codes to solve numerically the conservation and state equations, and to determine the loadings, strains, and the response of the primary containment during the excursion. By use of the appropriate constitutive relations for structural components, the deformation and response of these internal components can also be included in the calculation.

The latter approach has been used by Argonne National Laboratory in developing the Reactor Excursion Containment Codes (REXCO).⁴ The hydrodynamic version of the REXCO code (REXCO-H)⁵⁻⁷ has been applied to the conceptual design study of FFTF vessel head-cavity system, evaluation of coolant-impact effects on the reactor cover,⁸ preliminary safety analysis of the FFTF,⁹ design study of the LMFBR demonstration plant, and post-accident heat removal in LMFBR.¹⁰ This report describes the final analysis of the response of the FFTF primary system to an HCDA of 150 MW-sec using the latest version of the REXCO code (REXCO-HEP),¹¹ which treats not only the hydrodynamics, but also the elastic and plastic deformations of the reactor structures and components.

To make the report self-contained, the basic equations and numerical techniques used in the REXCO-HEP code are described. The mathematical model of the FFTF reactor is discussed in detail, particularly in the areas of modeling of reactor internals and extending the time range for which reliable calculation can be made. The basic assumptions, limitations, and conservatism of the model are also discussed. Finally, the results of the analysis are described in detail.

II. DESCRIPTION OF THE REXCO-HEP CODE

A. Basic Equations

1. Governing Equations for Elastic-Plastic Materials. Solid materials inside the reactor containment are treated as elastic-plastic materials. In this report, we consider only a cylindrical reactor with axial symmetry, that is, there is no motion in the circumferential θ direction and no variables of the system depend upon θ . Let the distance along the axis of symmetry be denoted by z , and let r denote the radial distance. Denote the Lagrangian coordinates by R and Z , and define the Lagrangian coordinates to be the position of the material at $t = 0$. The actual position r and z of the materials at a later time are dependent variables that are functions of (R, Z, t) . The other variables, density, pressure, etc., are also functions of (R, Z, t) . The momentum equations are

$$\begin{aligned} \ddot{r} &= \frac{1}{\rho} \left[-\frac{\partial(P-s_{rr})}{\partial r} + \frac{\partial\sigma_{rz}}{\partial z} + \frac{s_{rr} - s_{\theta\theta}}{r} \right] ; \\ \ddot{z} &= \frac{1}{\rho} \left[-\frac{\partial(P-s_{zz})}{\partial z} + \frac{\partial\sigma_{rz}}{\partial r} + \frac{\sigma_{rz}}{r} \right] , \end{aligned} \quad (1)$$

where ρ is the density, $P = p + q$ (with p the mean pressure and q the pseudoviscous pressure), s_{rr} , $s_{\theta\theta}$, and s_{zz} are the deviatoric component of the radial, circumferential, and axial stresses, respectively, σ_{rz} is the shearing stress, and the $(\dot{})$ denotes time differentiation along the particle path.

The energy equation is

$$\dot{E} = -P\dot{V} + V(s_{rr}\dot{e}_{rr} + s_{zz}\dot{e}_{zz} + s_{\theta\theta}\dot{e}_{\theta\theta} + \sigma_{rz}\dot{e}_{rz}) , \quad (2)$$

where V is the specific volume, and $\dot{e}_{rr}$, $\dot{e}_{zz}$, $\dot{e}_{\theta\theta}$, and $\dot{e}_{rz}$ are the strain-rate components, defined as

$$\dot{e}_{rr} = \frac{\partial\dot{r}}{\partial r} ; \quad \dot{e}_{zz} = \frac{\partial\dot{z}}{\partial z} ; \quad \dot{e}_{\theta\theta} = \frac{\dot{r}}{r} ; \quad \dot{e}_{rz} = \frac{\partial\dot{z}}{\partial r} + \frac{\partial\dot{r}}{\partial z} . \quad (3)$$

The conservation of mass can be stated very simply in terms of strain-rate components as

$$\rho^{-1}\dot{\rho} = -(\dot{e}_{rr} + \dot{e}_{\theta\theta} + \dot{e}_{zz})$$

or

$$\frac{\dot{V}}{V} = \frac{\partial\dot{r}}{\partial r} + \frac{\partial\dot{z}}{\partial z} + \frac{\dot{r}}{r} . \quad (4)$$

In a Lagrangian formulation, volume elements are defined by material points, so that mass is conserved implicitly.

The equation of state allows the strain increments calculated by Eq. 3 to be converted into stresses. For elastic-plastic materials, the stress-rate components up to the elastic limit are calculated from

$$\begin{aligned}\dot{s}_{rr} &= 2\mu \left(\dot{e}_{rr} - \frac{1}{3} \frac{\dot{V}}{V} \right) + \delta_{rr} ; \\ \dot{s}_{zz} &= 2\mu \left(\dot{e}_{zz} - \frac{1}{3} \frac{\dot{V}}{V} \right) + \delta_{zz} ; \\ \dot{s}_{\theta\theta} &= 2\mu \left(\dot{e}_{\theta\theta} - \frac{1}{3} \frac{\dot{V}}{V} \right) ; \\ \dot{\sigma}_{rz} &= \mu (\dot{e}_{rz}) + \delta_{rz} ,\end{aligned}\tag{5}$$

where μ is the shear modulus, and δ_{rr} , δ_{zz} , and δ_{rz} are the correction factors for rotation. For stresses beyond the elastic limit, the von Mises yield criterion is employed:

$$s_{rr}^2 + s_{zz}^2 + s_{\theta\theta}^2 + 2\sigma_{rz}^2 - \frac{2}{3} (\sigma_o)^2 = 0 ,\tag{6}$$

where σ_o is the yield stress of the given material under uniaxial stress conditions.

2. Governing Equations for Fluids. Fluids are assumed to be compressible but nonviscous. The conservation equations become

$$\begin{aligned}\ddot{r} &= - \frac{1}{\rho} \frac{\partial P}{\partial r} ; \\ \ddot{z} &= - \frac{1}{\rho} \frac{\partial P}{\partial z} ; \\ dE &= -PdV ;\end{aligned}\tag{7}$$

$$\frac{\dot{V}}{V} = \frac{\partial \dot{r}}{\partial r} + \frac{\partial \dot{z}}{\partial z} + \frac{\dot{r}}{r} .$$

The equation of state is assumed to have the form

$$p = f(V, E) .\tag{8}$$

If the value of σ_0 in Eq. 6 is set equal to zero, the stress deviators will be equal to zero automatically, and Eqs. 1 and 2 will reduce to the governing equations for fluids.

3. Governing Equations for Shell Structures. In an LMFBR, the reactor vessel is normally made of thin steel shells. If the reactor vessel is to be treated as an elastic-plastic solid material, the thickness of the vessel wall will have to be divided into at least 3 or 4 Lagrangian zones. Large numbers of Lagrangian meshes will be used in the numerical analysis, even for a simple configuration. Therefore, as an option in the REXCO-HEP, the reactor vessel can be analyzed as thin shell structures.

The equations of equilibrium for a shell of revolution undergoing large deflections are

$$\begin{aligned} \frac{\partial}{\partial s} \left[N_\phi r \cos \phi \right] - \frac{\partial}{\partial s} \left[Q_\phi r \sin \phi \right] - N_\theta + p r \sin \phi - m r \ddot{r} &= 0 ; \\ \frac{\partial}{\partial s} \left[N_\phi r \sin \phi \right] + \frac{\partial}{\partial s} \left[Q_\phi r \cos \phi \right] - p r \cos \phi - m r \ddot{z} &= 0 ; \\ \frac{\partial}{\partial s} \left[M_\phi r \right] - M_\theta \cos \phi - Q_\phi r &= 0 , \end{aligned} \quad (9)$$

where s is the length of the shell along the meridian, measured from the vertex of the shell, m the mass of the shell per unit area, ϕ the angle of inclination of the element with respect to the r -direction, p the pressure, N_ϕ and N_θ two tangential stress resultants, Q_ϕ the transverse stress resultant, and M_ϕ and M_θ the two stress couples. The thickness of the shell is idealized by layers of subshells that can carry only normal stresses in the planes parallel to the tangential plane of the shell structure. These subshells are connected by the material which carries only shears. The vessel material is considered to be elastic-plastic, strain-hardening, and strain-rate sensitive. The strain-hardening shell is represented by a model in which the thickness of the subshell is further decomposed into subregions of elastic-perfectly-plastic materials having different yield stresses, but common strains. The von Mises yield condition and the incremental strain theory of plasticity are used.

B. Equation of State of the Media

As stated in the previous section, the solution of the conservation equations requires an equation of state. To describe the behavior of the reactor materials, particularly in the reactor core and under high-temperature conditions, different equations of state are needed. The equations of state which have been built in the REXCO-HEP code are:

(a) MARS equation for vaporizing core (APDA-198):

$$p = A \exp \left(- \frac{B}{T + T_d} + C \right) ;$$

(b) pressure as a function of volume (V/V_0) in tabulated form:

$$p = f\left(\frac{V}{V_0}\right) ;$$

(c) pressure as a function of time (t) in tabulated form:

$$p = f(t);$$

(d) Mie-Grüneisen:¹²

$$p = p_H + \frac{\gamma}{V} (E - E_H) ;$$

(e) Murnaghan:¹³

$$p = \frac{B_0}{B'_0} \left[\left(\frac{V_0}{V} \right)^{B'_0} - 1 \right] ;$$

(f) ideal gas:

$$p = \frac{(\eta - 1)E}{V} ;$$

(g) TNT explosives:¹⁴

$$p = \frac{E}{\beta V} + \alpha \left(\frac{1}{V} \right)^\eta \left[1 - \frac{1}{\beta(\eta - 1)} \right] .$$

In these equations,

- p = pressure;
- V = specific volume;
- V_0 = original specific volume;
- T = temperature;
- T_d = constant;
- A, B, C, D = constants;
- E = specific internal energy;
- p_H, E_H = pressure and internal energy along the Hugoniot curve;
- γ = Grüneisen's coefficient;
- η = isentropic exponent;
- α, β = constant;
- B_0, B'_0 = bulk modulus and its derivative.

Equations related to fuel-coolant interaction, which have been used in the REXCO-HT, an augmented version of REXCO-H for heat-transfer calculations, have not been included in the REXCO-HEP code.

C. Numerical Technique

In the numerical analysis, all equations are first expressed in material coordinates and then set into numerical form by finite-difference equations. Shock discontinuities and other numerical oscillations are eliminated by the use of artificial viscosities. The numerical solution of these finite-difference equations is done with the IBM-360 Model-195 computer.

For each problem, the code computes the accelerations, velocities, displacements, change of volumes, densities, strains, pressures, and specific energies at every spatial point for a specific time interval. For elastic-plastic materials, the code also calculates the deviatoric stresses and distortion energies. These computations are repeated for every time interval until the maximum time specified is reached, the reactor vessel ruptures, or the vessel head-holddown device fails, whereupon the computation ceases. Figure 1 is a flow chart of the REXCO-HEP code.

Fig. 1.
REXCO Flow Chart.
ANL Neg. No. 900-1654.

D. Artificial Viscosity

An artificial viscosity q was first introduced by von Neumann and Richtmyer¹⁵ to permit numerical calculations of shock hydrodynamics by replacing the discontinuous pressure jump across a shock by a rapid but continuous pressure change. This device has also proved to be very useful in preventing oscillatory solutions in the numerical computations. Four types of q are available in the REXCO-HEP code: linear, quadratic, Navier-Stokes, and rotational.

E. Mesh Regularization

The disadvantage of using the Lagrangian codes is the limitation imposed on the distortions of the Lagrangian zone. In some problems, particularly in the case of low-energy excursions, the zone distortions may increase and become extreme when the calculations are extended to cover the entire excursion. Therefore, it is necessary to have some means to eliminate or minimize the zone distortions so that reliable calculations can be obtained when the computation time is being extended.

Recent studies¹⁶⁻¹⁸ reveal that some severe distortions of the Lagrangian zones are not physically real. These distortions are caused by the method of solution rather than by the physics of the problem. For instance, the most frequently occurring "hour-glass" distortions of a quadrilateral mesh are not physically real, but they are indeed mathematically the nontrivial homogeneous solutions of the three strain equations in which the strains are calculated from the motion of the four corners. The zone sides of the quadrilateral increase and decrease alternately in such a way that the volume of the mesh remains unchanged; therefore, no restoring force is introduced. Once this mode of distortion starts, it grows until the numerical computations become unstable. Therefore, for this type of zone distortion, it is perfectly justifiable to introduce a scheme to control or regulate these nonphysically-real distortions.

LASL developed a mesh-regularizing scheme¹⁶ for incompressible flows. A damping force was introduced that tends to keep a mesh vertex in the center of mass of its eight adjacent neighboring vertices. Hoskin¹⁹ has incorporated the LASL scheme into a compressible Lagrangian code, ASTARTE. A different mesh-regularization scheme is used in the REXCO-HEP, which utilizes an artificial rotational force to prevent growth of the non-physical distortions. The magnitude of the rotational force is proportional to the rate of the relative rotation of the opposite zone sides. This scheme has been tested successfully in many problems. It can reduce and minimize the zone distortions in the numerical calculations, and thus extend the calculations to much longer times.

F. Verification of Code

As stated earlier, the differential equations in the REXCO code are set into numerical form by finite-difference equations and then solved numerically with the computer. How closely the numerical solution approximates the true solution of the differential equations depends upon a number of considerations involving the mathematical model, types of loadings, the ranges of time to be covered by the numerical analysis, and the stability

and convergence of the numerical techniques used. Therefore, to test the overall reliability of the code performance, comparisons must be made with experimental results.

REXCO predictions have been compared with many experimental excursion data. Predictions of the pressure loading generated by chemical high-explosive charges have been compared with four sets of experiments by Ash and Julke²⁰ using the REXCO-H code. The results of their comparisons indicate that REXCO-H can predict accurately the early-time pressure loadings generated in small-model experiments using chemical explosives such as RDX/TNT and PETN/TNT. Not only can experimental data be reproduced with such a computer code, but through the use of the code as a research tool detailed insights can be gained into the relative effects of parameter variations.

Further comparisons, with emphasis upon the deformations of the vessel wall produced by the pressure loads, have been made.²¹ Computations of the deformation of the containment-vessel wall caused by pressure loads generated by high-explosive charges were compared with the results of experiments conducted by the Naval Ordnance Laboratory. The computations of deformations in the upper vessel region resulting from coolant-slug impact were verified by comparison with the SL-1 accident data. The comparisons further demonstrate that the structural response to a high-explosive charge, as well as slug-impact loading, can be predicted by the REXCO-H code.

Of all the experiments analyzed, including the SL-1 accident, the most decisive for the purposes of the comparison was the UKAEA bare explosive charge in water.³ The pressure waves transmitted through the water were measured directly by a battery of piezoelectric gauges mounted in the wall of the tank. Because of the simplicity of the experiment, possible ambiguities were minimized in the description of the material behavior and processes. The detonation process and the equations of state for the RDX/TNT and the water are reasonably well-known, so that the correlation between the experimental data and code results can be expected to provide a true measure of the basic code performance. Although the comparison of the code-predicted pressure-time variation at gauge-3 position with the values measured in the experiment showed a good agreement, the peak pressure in the REXCO-H prediction was about 19% higher than the measured value of 1.6 kbar. Since the tank wall in the REXCO-H analysis was assumed to be rigid, the computed pressures were expected to be higher. However, to verify the code, it is necessary that this rigid-wall boundary condition be removed from the computer calculation so that the closeness of approximation of the numerical solution to the true solution can be fully assessed.

The REXCO code has since been extended to treat elastic-plastic materials. The new REXCO-HEP version was applied to the same experiment with the same input except that the walls were treated as an elastic-plastic medium. In the experiment, the base plate of the tank was 3-in.-thick steel, and the composite vessel wall was made of 1-in.-thick wall and five 3-in.-wide, 1-1/2-in.-thick reinforcing rings. The mathematical model is shown in Fig. 2a, in which the composite vessel wall is given an equivalent thickness of 1.9375 in. Both the base plate and vessel wall are partitioned into three grid zones. The grid distortion at $t = 243.4 \mu\text{sec}$ is shown in Fig. 2b. The pressure trace at gauge-3 position as computed with REXCO-HEP is shown in Fig. 3. Because of the wall motion due to both the bending and

Fig. 2.
Mathematical Model of the Bare-charge Experiment and Grid Distortion at $t = 243.4 \mu\text{sec}$. ANL Neg. No. 900-2243.

Fig. 3.
Comparison of Computed and Measured Pressure Loading at Gauge-3 Position (Bare Charge). ANL Neg. No. 900-3006.

compression deformation modes, the pressure is lower than that of the rigid wall. The peak pressure is reduced from 1.9 to 1.76 kbar. This indicates that the REXCO code can predict the pressure loadings generated by wave propagation from releases of energy from high explosive to within 10% deviation of the experimental measured value.

Since the energy release in an HCDA is very different from that of a high explosive, the question remaining to be answered is how well the code will predict the response to a hypothetical core-disruptive accident postulated for an LMFBR.

From the available experimental data, it appears that the UKAEA confined-charge test³ is the closest simulation of this kind. The breeder structure surrounding the core was simulated in the scaled model, and the

pressure loading on the vessel wall was about the same magnitude produced by a nuclear excursion. Furthermore, the time needed for the water slug, driven upward by the direct shock and the expansion of the explosive gas bubble, to contact the reactor cover is considerably longer than that from a bare-charge test. Therefore, to test the performance of the code for lower-pressure excursions and for longer time ranges - for example, up into the millisecond range for the high-explosive model tests - the REXCO-HEP code was applied to analyze that experiment.

The mathematical model is shown in Fig. 4a; the grid deformations at various times are shown in 4b, c, and d, respectively. It is very important to note that the nonphysically-real zone distortions have been virtually eliminated in the REXCO-HEP calculations by the mesh-stabilization scheme. The code calculation was terminated at $t = 1.552$ msec. It should be mentioned that this termination was not caused by the limitation of the code; the calculation could have continued to even longer times if desired. Figure 5 shows the calculated and measured pressure history at Gauge-3 position. The predicted peak pressure and the width of the pulse are in good agreement with the experiment. However, the arrival time of the pressure wave in the REXCO-HEP calculation is slightly delayed compared to the experimental result. This is probably due to the mathematical model used for the porous material, which allows the wave to be transmitted only after the porous material is fully recompacted. It is believed that a recalculation with a more sophisticated model for the porous material could eliminate this time delay. For the purpose of this comparison, the arrival time of the computed pressure pulse in Fig. 5 has been adjusted to account for this delay. The computed pressure history at the Gauge-10 position on the tank cover is shown in Fig. 6. The computed peak pressure is 1.207 kbar, whereas the measured peak pressure was 1.034 kbar. This indicates that the code can also be used to predict the slug-impact loads which occurred at a much later time during the excursion.

Recently, Stanford Research Institute (SRI) has developed a shockfree energy source for use in scaled-model tests to simulate a nuclear excursion.²² The source consists of a charge of a ratio of 65/35 by weight of PETN powder and glass microballoons contained in a canister of stacked and spaced steel rings held between steel end plates. It produces gas with pressure and expansion characteristics similar to those from code calculations of a sodium-vapor explosion in fast-reactor hypothetical accidents. The REXCO-HEP code was used to determine the gas characteristics of this shockfree energy source. The experiments were evaluated by comparison of observed data with REXCO analysis.²³ Agreement of computed and measured data is remarkably good.

After the energy source had been completely characterized, a series of experiments²⁴ was carried out by SRI using simple and complex scaled models to investigate the response of the FFTF reactor under the postulated accident. In order to verify further the validity of the REXCO code for postulated accidents, REXCO-HEP was used to predict the test results. Comparison of simple-model experiments with REXCO calculation was performed by Nagumo;²³ comparison of complex-model experiments was performed by T. Marciniak, J. Gvildys, G. Nagumo, and J. Ash.²⁵ In all comparisons, REXCO calculations are in good agreement with the test results. It should be mentioned that the SRI complex models were designed to simulate as much as possible the details of the Fast Test Reactor. Detail features provided

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Fig. 4. Mathematical Model of the Confined Charge Experiment and Grid Distortions.

Fig. 5. Comparison of Computed and Measured Pressure Loading at Gauge-3 Position (Confined Charge). ANL Neg. No. 900-3005.

Fig. 6. The Computed Pressure Loading at Gauge-10 Position (Confined Charge). ANL Neg. No. 900-3016.

in the test configuration included (1) vessel-support arms, (2) core barrel, (3) radial shield, (4) core-support structure, (5) thermal liners and baffles, (6) detailed vessel-head configuration, including penetrations, holddown bolts, and crushable material on the bottom surface, (7) instrument trees, (8) fission-gas plenum, and (9) in-vessel fuel-handling machines. In the 1/10th-scale model, piping loops were included. Nevertheless, the agreement of computed and measured data for the vessel deformation and pressure loading is very good. At the core midplane, the maximum strain measured was 1.06% for the 1/30th-scale model and 1.20% for the 1/10th-scale model, whereas the calculated values were 1.0% for both models. At the vessel top, the maximum strain measured was 2.23% for the 1/30th model and 1.88% for the 1/10th-scale model, whereas the respective calculated values were 3.4% for the 1/30th model and 3.2% for the 1/10th model.

The smaller deformation observed in the experiments at the vessel top is probably attributed to the fact that the experimental models were not leak-proof. A considerable amount of water was lost after slug impact. The computed pressure history at the location of the outlet nozzle wall is shown in Fig. 7 together with the experimental data. Since the nozzle

Fig. 7. Comparison of Computed and Measured Pressure Loading at Outlet Nozzle (1/10th Model). ANL Neg. No. 900-3018.

opening was excluded in the REXCO analysis, the calculated pressure loading was expected to be slightly higher than the measured. This computation further demonstrates that the REXCO code can be applied with confidence to compute the consequences of an HCDA in a very complex reactor configuration if provided with an initial distribution of energy in the core and with accurate equations of state for the core and surrounding structures.

III. ANALYSIS OF THE FFTF PRIMARY SYSTEM RESPONSE TO AN HCDA

A. Mathematical Model

The FFTF reactor, as can be seen from Fig. 8, is very complex. No computer code, no matter how sophisticated, can include all the details of the reactor in the mathematical model. Therefore, to perform a manageable computer analysis, the representation of the FFTF reactor must be simplified. The important question is to what degree the representation of the FFTF reactor can be simplified so that the model accurately describes the response of the FFTF reactor under the HCDA loads.

The general approach to the mathematical model is to incorporate, to the extent possible, the correct material properties and equations of state of the reactor materials, especially for critical materials such as the vessel and core barrel. Figure 9 shows the mathematical model used in the REXCO analysis. Features included are (1) the vessel and thermal liner, including the vessel-support ring, head flange, and ellipsoidal bottom, (2) the core-support structure, (3) the core barrel, (4) the radial and axial shields, (5) the radial and axial reflectors, (6) the fission-gas plenum, (7) the core, and (8) the shield plug and holddown bolts. Several of the internal details, such as the instrument tress (IV), in-vessel fuel-handling machines (IVHM), as well as the details of the core-support structure, are ignored in the mathematical model.

Modelings of the vessel and core barrel are kept as accurate as the code allows. The flanges and rings on the vessel and core-barrel walls, as well as the thermal liner, are included and treated as thin shells of revolution. The inclusion of the core support in the calculation is accomplished by shaping those Lagrangian zones which represent the core-support structure to conform to the actual configuration. The mass of the core support is taken to be the same as for the actual configuration, and the structure is treated as an elastic-plastic solid material. Shields, reflectors, and fission-gas plenum in the mathematical model have the same configuration, mass, compressibility, and wave-propagation properties as for the actual material, but they are considered to have no tensile strength in the axial and circumferential directions. This more closely represents the segmented nature of the shields and reflectors, which cannot resist hoop stresses. The shield plug is modeled as a rigid, solid circular plate, held to the ground by holddown bolts. Since holddown bolts constitute a part of the primary boundary, it is believed that some conservatism is needed in the design to prevent rupture of the bolts during the slug impact. It is believed that omission of the head deformation would give a somewhat greater impact force on the head cover and thus cause a greater straining of the holddown bolts.

The omission of the instrument trees and the in-vessel fuel-handling mechanisms in the mathematical model is based upon the results of the SRI tests,²⁴ which show that only a very small amount of energy is deposited in these structures. Since these structures are asymmetric, they cannot be faithfully modeled in the two-dimensional analysis and are therefore excluded. Also excluded in the mathematical model are the openings of the inlet and outlet nozzles, again a limitation of the two-dimensional analysis. It is believed that a somewhat conservative approach would be to

Fig. 8. FFTF Reactor Configuration.
ANL Neg. No. 900-2705.

Fig. 9. Mathematical Model of the FFTF Reactor.
ANL Neg. No. 900-1352.

neglect these openings in the analysis, so that the calculated pressure pulses on the vessel wall are higher.

B. Excursion Model

It was postulated that if a small amount of coolant is still in the core during the power excursion, the molten fuel could come into contact with the coolant, causing a rapid heating of a relatively small volume of sodium and producing a sodium-vapor explosion. Thus, the expansion of the high-pressure sodium vapor against the surroundings would become the mechanism of producing mechanical damage to the system. The sodium-expansion model used in the REXCO-HEP analysis is the SOCOOL²⁶ model, which was provided by HEDL for evaluation of the mechanical work resulting from the HCDA postulated for the FFTF reactor. The mechanical work potential due to the expansion of the sodium vapor to a pressure of 1 atm has a magnitude of 150 MW-sec. The input of this analysis is listed in Appendix A.

C. Numerical Results

The outputs of the computed code are displacements, velocities, pressures, specific internal energies, densities, strains, stresses, strain energies, energy partition, and forces on the reactor cover and core-support structure. They are given in Appendix B.

Of importance to the safety analysis are the results for: (1) core-barrel deformation, (2) vessel-wall deformation, (3) pressure at inlet and

outlet nozzles, (4) loads on core-support structure, (5) slug-impact force, (6) energy partition at slug impact, (7) velocity and displacement of the upper vessel wall, (8) deformation of the holddown-bolt system, and (9) ultimate disposition of the excursion energy. They are described in greater detail below.

As mentioned earlier, the expansion of the high-pressure sodium vapor is the mechanism for producing mechanical damage to the system. The sequence of events occurring during the excursion is as follows. As the sodium vapor expands, it first deforms the core-surrounding structures (reflectors, shields, etc.). As it expands further, it pushes the core-support structure downward, deforms the core barrel and vessel wall radially, and accelerates the liquid sodium above the core upward. When the slug of sodium, after being accelerated upward by the expanding core, comes into sudden contact with the reactor cover, a large impact force is exerted on the head cover and upper vessel wall. The holddown bolts and upper vessel wall are then deformed plastically; thus, the energy of the coolant is dissipated in strain energies of the bolts and vessel wall. Finally, the system regains dynamic equilibrium.

Figure 10 is a series of computer-generated reactor configurations at various times during the excursion. These configurations show how the core-surrounding structures are deformed, and how the deformations of the core barrel, vessel wall, and other structures adjacent to the core become progressively larger with time. Figure 10 also shows how the coolant slug is being pushed upward until it comes in contact with the reactor cover and how the upper vessel wall is deformed. The overall flow of the coolant can be followed visually from these configurations.

It is interesting to note that at the time of the slug impact ($t = 40.6$ msec), the core barrel and the vessel wall at the core region have already deformed to their maximum, but no deformation of the wall at the vessel top has as yet taken place; deformation at the top occurs only after the coolant slug contacts the reactor cover. The maximum deformation of the core barrel is about 6.1%, which occurs at $t = 31.9$ msec. The maximum deformation of the vessel wall adjacent to the core is about 0.57%. The maximum deformation of the upper vessel wall resulting from the slug impact with the cover is about 3.5%. Because of the presence of a heavy flange at the top of the vessel wall, the maximum deformation occurs at approximately two zones below the reactor cover. It is also very interesting to note that, although the mesh deformation adjacent to the core is significant, the major part of the coolant above the core rises as a unit with very little mesh distortion. The velocity distribution of the coolant body is quite uniform. Because of the presence of the massive core-support structure, the downward motion of the coolant is very small, so very little deformation occurs at the lower part of the vessel wall.

It should be mentioned that even with the mesh-regularizing scheme in the code, large mesh distortions can still occur in the core region, especially at the core barrel (see Fig. 10e). To overcome this, the distorted zones adjacent to the core barrel have been rezoned. The effect of rezoning can be seen from Fig. 10f.

Also of interest is the partition of energy, which is shown in Fig. 11 as a function of time. It shows how the core internal energy is transformed

Fig. 10. Reactor Configurations at Various Times during Excursion.
ANL Neg. No. 900-2712.

into other energies. The work energy released from the core is first transformed into radial and axial kinetic energy of the coolant. Because of the existence of the heavy core-support structure, the downward kinetic energy of the coolant is very small. The radial kinetic energy of the coolant is later transformed into strain energy of core barrel and vessel wall (core region). The core-barrel strain energy is increasing progressively with time and leveling off after it reaches the dynamic equilibrium. The strain energy of the vessel wall before the slug impact is quite small. After the coolant slug impinges on the reactor cover, the upward axial energy of coolant is transformed into internal energy of coolant, into radial kinetic energy of coolant, and then into strain energy of vessel wall (upper portion) and energy of plug and hold-down bolts. At the time of incipient slug impact, the work energy released is 67.0 MW-sec, and the corresponding

Fig. 11. Partition of Energy as a Function of Time. ANL Neg. No. 900-2972.

vapor pressure in the core is about 24 bars. The partition of the energy released is 66.6% upward kinetic energy, 0.2% downward kinetic energy, 6.3% radial kinetic energy, 17.8% core-barrel strain energy, 7.2% vessel strain energy, and 1.9% coolant internal energy.

Since the primary loop is a part of the primary boundary, its containment capability must also be assessed. Pressure pulses at the inlet and outlet nozzles are used as input to the analysis of loads on primary-loop components. Figure 12 shows the pressure loadings at outlet and inlet

Fig. 12. Pressure Loading at Inlet and Outlet Nozzles. ANL Neg. No. 900-2714.

nozzle openings obtained from the REXCO-HEP analysis. The maximum pressure at the outlet nozzle from the core-sodium-vapor expansion is about 50 bars; the maximum pressure at the inlet nozzle is about 30 bars. The lower pressure in the inlet-nozzle wall is due to the presence of a massive core-support plate that prevents the coolant slug from moving downward. It should be noted that the shapes of the two pulses are also different. The peak pressure at the outlet nozzle occurs at a much earlier time than that at the inlet nozzle. This may become an important factor in the evaluation of loads imposed on primary-loop components. It should be mentioned that pressure peaks of about 80-90 bars have been observed at the outlet-nozzle wall after $t = 43$ msec (not shown in Fig. 12). These are due to reflected pressure pulses produced by the slug impact. However, these reflected pressure waves from the slug impact do not produce noticeable pressure peaks at the inlet-nozzle wall.

The high pressures generated in the hypothetical accident also act on the core-support structure. These loads cause forces to be transmitted up the vessel wall to the vessel-support straps. The integrity of the support straps is very important, since the downward acceleration of the reactor vessel is to be arrested by these devices. For this reason, the REXCO-HEP analysis also provides the downward forces on the core support, as shown in Fig. 13. It is very interesting to note that the downward force on the

Fig. 13. Downward Thrust on Core-support Structure.
ANL Neg. No. 900-2715.

upper surface of the core-support structure, unlike the pressure loading at the nozzle-wall openings, has a clearly visible period of oscillation. The time of the period is about 3 msec, which is very close to the natural frequency of the core barrel.

The expansion of the high-pressure sodium vapor pushes a coolant slug toward the cover. Upon impact, energy is transferred from the slug to the cover and upper vessel wall. To evaluate the cover stresses and deformations, holddown-bolt response, loading on equipment which penetrates or attaches to the vessel head, and effects of missiles, the loading history on the vessel head is needed.

Figure 14 is the cover-loading history as obtained from the REXCO-HEP analysis. The slug force consists of a large triangular-shaped impulse, which lasts for about 2 msec, and a long-duration, oscillating residual pressure force. The triangular-shaped impulse is caused by the sudden contact of the coolant with the cover head. Because the distribution of velocity in the coolant body is not exactly uniform, the peak slug force is smaller than that produced by a uniform-velocity coolant slug. The magnitude of the peak slug force is 85.3×10^{12} dynes, which occurs at

Fig. 14. *Slug-impact Force as a Function of Time.*
ANL Neg. No. 900-2716.

$t = 42.102$ msec. The residual pressure forces following the initial impact are due to the continuous expansion of the core-sodium vapor which pushes the coolant slug to exert further pressure on the cover. The total work energy released from the core-sodium vapor at $t = 92.774$ msec is 84.16 MW-sec, of which 17.16 MW-sec is released after the slug impact.

The distribution of energy at that instant is: (1) upward kinetic energy, 8.11 MW-sec; (2) downward kinetic energy, 1.32 MW-sec; (3) radial kinetic energy, 1.31 MW-sec; (4) core-barrel strain energy, 11.95 MW-sec; (5) vessel strain energy, 38.11 MW-sec; (6) coolant internal energy, 7.97 MW-sec; and (7) energy imparted to reactor head, 15.39 MW-sec, totaling 84.16 MW-sec. The gas pressure in the core is about 12-15 bars. The head has moved upward 14.8 cm; the axial velocity of the head at that instant is 111 cm/sec. The energy of 15.39 MW-sec imparted to the reactor head can be further partitioned into: (1) kinetic energy of head, 0.39 MW-sec; (2) potential energy of head, 0.89 MW-sec; (3) holddown-bolt strain energy, 14.11 MW-sec, totaling 15.39 MW-sec.

The primary-containment system is already in dynamic equilibrium at $t = 92.774$ msec. The unreleased HCDA work energy will be retained in the core for a relatively long period of time if the sodium is not allowed to spill out of the primary containment. This is also true for the sodium kinetic energy. The sodium will be in vibratory motion for a long time until it is finally damped out by the viscous frictional force. The additional energy imparted to the reactor head and vessel wall will be very small.

From the results of the REXCO-HEP analysis, it can be concluded that the reactor vessel will remain intact in the 150 MW-sec HCDA, and the post-accident heat can be continuously removed from the damaged core. A large safety margin is also provided in the holddown-bolt design, and the cover will not become a missile.

IV. CONCLUSIONS AND RECOMMENDATIONS

It has been demonstrated that the REXCO-HEP code can predict accurately the response of the primary containment to high explosives, as well as to HCDAs, and can give guidance as to the effects of such accidents in a fast-reactor system. The good agreement between the REXCO predictions and the SRI complex-model test results further demonstrates that the REXCO-HEP can

be applied with confidence to compute the consequences of an HCDA in a very complex reactor configuration, if provided with an initial distribution of energy in the core and with accurate equations of state for the core and surrounding structures.

From the results of the REXCO analysis, it can be concluded that the reactor vessel and the core-support structure will remain intact in the 150 MW-sec HCDA. A large safety margin is also provided in the holddown-bolt design, and the cover will not become a missile. The pressure predictions obtained from the REXCO analysis at the inlet and outlet nozzles are conservative. The containment capability of primary-loop components can be assessed based upon these loadings.

To improve computer results, a better understanding of the energy-release mechanisms and more reliable equation-of-state data for the core materials, the fission gas, and the sodium coolant over the appropriate pressure and temperature ranges are needed. Also needed are the dynamic properties of the reactor structural materials under very rapid loading and proper modeling techniques of the complicated structures, such as the core-support structure and the reactor cover head. REXCO will provide the designer with a more useful tool as such information becomes available.

It is believed that extensive explosive-testing programs will not be necessary to assess the containment capability of reactor systems. Future tests may be needed only for rather unusual reactor or primary-system configurations. Also, understanding of the behavior of individual internal components and their effects on the primary system may require testing, so that appropriate mathematical models can be formulated for these components.

APPENDIX A. Complete Input-data Listing

The computer input of the FFTF analysis is listed in the following pages.

```

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  1      1      100      50      1
  17
  11      5      11      6      11      23      11      25      -12      5      -12      7
-12      23      -12      26      112      5      112      7      112      23      202      211
  702      711      1202      1211      1202      1211      1205      1206      2205      2206
  0.0      30.48      60.96      91.44      121.92      152.40      182.88      213.36
243.84      274.32      304.80
  0.0      45.72      91.44      137.16      182.88      228.60      274.32      304.80
335.28      365.76      396.24      426.72      457.20      487.68      518.16      548.64
579.12      609.60      640.08      670.56      701.04      732.4725      763.905      795.3375
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1078.23      1109.66251141.095      1172.52751203.96
  12
  2      11      2      37      2
  2      11      8      11      13
  2      4      9      11      14
  2      4      12      13      15
  2      3      14      14      5
  2      3      15      17      1
  2      3      18      18      5
  2      3      19      21      7
  4      4      14      21      6
  5      6      12      21      16
  2      6      12      12      12
  2      12      2      11      0
  13
  1
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  .024016      1.      24.
  .204377      .004666      .203516      .005134      .202655      .005602      .162124      .008063
  .131726      .010524      .101327      .014004      .091195      .015554      .081062      .017404
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  7.85      46.
  1000.      .7295      950.      .735      900.      .7402      850.      .746
  800.      .7523      750.      .7585      700.      .7655      650.      .7726
  600.      .781      550.      .7896      500.      .799      450.      .8094
  400.      .821      350.      .8345      320.      .843      300.      .8475
  280.      .8526      260.      .8585      240.      .8655      225.      .8717
  210.      .8785      195.      .8862      180.      .8945      170.      .9012
  160.      .9085      155.      .9125      150.      .917      145.      .9217
  140.      .9266      135.      .932      131.      .937      115.      .9445
  90.      .9565      80.      .9615      70.      .9665      60.      .9714
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  -5.      1.002      -5.0      1.2

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3.136^{1.2} .0 .0 .0 .1⁵⁰

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 1.2 .0 .0 .0 .1

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108.32	.5437	100.	.5482	90.	.5538	81.1	.55874
70.	.5675	62.	.574	56.66	.57849	50.	.5855
45.	.5915	40.	.598	35.04	.60495	30.	.6133
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6.744¹³ 40.209E9 3.59

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1.94395^{1.2} .0 .0 .0 .1

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5	2 91.44	9.144			0.808		2
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7	2 152.40	21.336			0.808		2
8	2 182.88	32.004			0.808		2
9	2 213.36	45.720			0.808		2
10	2 243.84	60.960			0.808		2
11	2 274.32	85.344			0.808		2
12	2 297.18	121.920			0.808		2
2	3 0,	44.196			0.808		2
3	3 30.48	45.720			0.808		2
4	3 60.96	48.768			0.808		2
5	3 91.44	54.864			0.808		2
6	3 121.92	60.960			0.808		2
7	3 152.40	70.104			0.808		2

8	3182,88	82,296	0,808	2
9	3213,36	96,012	0,808	2
10	3243,84	114,300	0,808	2
11	3274,32	135,636	0,808	2
12	3304,80	163,068	0,808	2
2	4 0,	91,440	0,808	2
3	4 30,48	92,964	0,808	2
4	4 60,96	94,488	0,808	2
5	4 91,44	99,060	0,808	2
6	4121,92	105,156	0,808	2
7	4152,40	115,824	0,808	2
8	4182,88	128,016	0,808	2
9	4213,36	144,780	0,808	2
10	4243,84	163,068	0,808	2
11	4274,32	182,880	0,808	2
12	4304,80	202,692	0,808	2
2	5 0,	137,160	0,808	2
3	5 30,48	138,684	0,808	2
4	5 60,96	140,208	0,808	2
5	5 91,44	143,256	0,808	2
6	5121,92	152,400	0,808	2
7	5152,40	163,068	0,808	2
8	5182,88	175,260	0,808	2
9	5213,36	190,500	0,808	2
10	5243,84	205,740	0,808	2
11	5274,32	224,028	0,808	2
12	5304,80	242,316	0,808	2
2	6 0,	182,880	0,808	2
3	6 30,48	182,880	0,808	2
4	6 60,96	182,880	0,808	2
5	6 91,44	185,928	0,808	2
6	6121,92	195,072	0,808	2
7	6152,40	207,264	0,808	2
8	6182,88	219,456	0,808	2
9	6213,36	231,648	0,808	2
10	6243,84	245,364	0,808	2
11	6274,32	259,080	0,808	2
12	6304,80	274,320	0,808	2
2	7 0,	228,600	0,808	2
3	7 30,48	228,600	0,808	2
4	7 60,96	228,600	0,808	2
5	7 91,44	233,172	0,808	2
6	7121,92	239,268	0,808	2
7	7152,40	249,936	0,808	2
8	7182,88	260,604	0,808	2
9	7213,36	272,796	0,808	2
10	7243,84	283,464	0,808	2
11	7274,32	294,132	0,808	2
12	7304,80	304,800	0,808	2
2	8 0,	274,320	7,85	3
3	8 30,48	274,320	7,85	3
4	8 60,96	274,320	7,85	3
5	8 91,44	274,320	7,85	3
6	8121,92	283,464	7,85	3
7	8152,40	291,084	7,85	3
8	8182,88	300,228	7,85	3
9	8213,36	309,372	7,85	3
10	8243,84	318,516	7,85	3
11	8274,32	327,660	7,85	3
12	8304,80	335,280	7,85	3

2	9	0.	304.800			7.85		3
3	9	30.48	304.800			7.85		3
4	9	60.96	304.800			7.85		3
5	9	91.44	304.800			7.85		3
6	9	121.92	312.420			7.85		3
7	9	152.40	318.516			7.85		3
8	9	182.88	326.136			7.85		3
9	9	213.36	332.232			7.85		3
10	9	243.84	338.323			7.85		3
11	9	274.32	344.424			7.85		3
12	9	304.80	350.520			7.85		3
2	10	0.	335.200			7.85		3
3	10	30.48	335.200			7.85		3
4	10	60.96	335.200			7.85		3
5	10	91.44	335.200			7.85		3
6	10	121.92	339.852			7.85		3
7	10	152.40	344.424			7.85		3
8	10	182.88	347.472			7.85		3
9	10	213.36	352.044			7.85		3
10	10	243.84	356.616			7.85		3
11	10	274.32	361.188			7.85		3
12	10	304.80	365.760			7.85		3
2	11	0.	365.760			7.85		3
3	11	30.48	365.760			7.85		3
4	11	60.96	365.760			7.85		3
5	11	91.44	365.760			7.85		3
6	11	121.92	367.937			7.85		3
7	11	152.40	370.114			7.85		3
8	11	182.88	372.291			7.85		3
9	11	213.36	374.468			7.85		3
10	11	243.84	376.646			7.85		3
11	11	274.32	378.823			7.85		3
12	11	304.80	381.000			7.85		3
1	2	11	4	0	6.1689E8	2	11	
					40.1.15703E14			
2	11	1249.68	4	2	1 38	344.80	4	2
2	2							
12	2		1	1	11	6.985	8.5725	72.0
8	12		2	2	11		5.25	
0								
27								
12	2	6.985	12	3	6.985	12	4	6.985
8	23		8	24		8	26	
8	29		8	30		8	32	
8	35		8	36		8	38	
12	10		12	11		8	22	
1.31005E9	.00084	8.95894E9	.400		7.85	.3		
1.58585E9	.00096	8.72190E9	.400		7.85	.3		
1	.0015	.25E14						
2.E7	0.	2.E7	0.	2.E7	0.	2.E7	0.	
1.	-2.	1.	-2.	1.	-2.	1.	-2.	
200.	-1000.	200.	-1000.	200.	-1000.	1.E13	0.	
1.E13	0.	1.E13	0.	1.E13	-2.E13	1.E12	0.	
1.E12	0.							

APPENDIX B. Computer Output

Because of the physical limitations of this report, it is not possible to present a complete set of the REXCO outputs. Some of the results are given in Figs. B.1-B.17 and Table B.I.

Fig. B.1.
Film Display of Grid Con-
figuration at $t = 0$.

Fig. B.2.
Film Display of Grid Config-
uration at $t = 39.91$ msec.

Fig. B.17.
Film Display of Grid Configuration at $t = 92.774$ msec.

TABLE B.I. Axial Velocity of Grid Points at t = 39.91 msec.

FFTF,DBA=150MWS,10*36,NEW M. FOR V.,C.B., CQ5(N)=.1 2000-2500 12/08/72

AXIAL VELOCITY OF GRID POINTS AT TIME = 0.3991000D-01 AND D-TIME= 0.1600000D-04 AT CYCLE-2500
MAXIMUM ABS. VALUE = 0.9136039D 04 SCALE FACTOR = 0.10D 01

R	2	3	4	5	6	7	8	9	10	11	12
Z											
38	1903	2030	2119	1986	1846	1771	1742	1738	1723	1781	1873
37	1995	2076	2128	1990	1826	1763	1741	1711	1727	1765	1839
36	2115	2146	2137	1999	1819	1758	1749	1692	1716	1774	1862
35	2172	2198	2162	2003	1818	1757	1755	1672	1695	1763	1850
34	2205	2239	2182	2022	1815	1765	1762	1647	1676	1756	1847
33	2252	2282	2207	2042	1821	1786	1769	1615	1665	1756	1843
32	2298	2325	2247	2063	1830	1799	1789	1588	1638	1716	1788
31	2361	2400	2303	2086	1835	1824	1805	1558	1610	1686	1770
30	2458	2513	2372	2103	1849	1852	1839	1535	1565	1649	1743
29	2623	2666	2462	2129	1862	1896	1872	1506	1523	1595	1684
28	2852	2894	2568	2148	1876	1940	1925	1468	1453	1506	1580
27	3243	3209	2702	2158	1884	2005	1981	1391	1341	1382	1448
26	3738	3630	2801	2160	1913	2095	2064	1217	1150	1165	1218
25	4410	4054	2836	2144	2009	2268	2097	863	791	831	874
24	5049	4481	2726	2226	2120	2498	2164	422	412	431	477
23	5817	4816	2918	2291	2233	2735	2222	447	180	94	94
22	5719	5664	3536	2554	2074	2318	2527	710	220	-28	-56
21	5908	6091	3269	2157	1694	1966	2993	332	121	-32	-60
20	6136	6407	2682	1685	1351	1672	3742	63	-20	-84	-101
19	6466	6563	1973	1266	1087	1428	4825	-156	-140	-144	-171
18	6838	6660	1289	898	833	1165	6651	-456	-208	-228	-250
17	4597	3640	693	564	559	865	9136	-154	-162	-235	-276
16	968	2977	467	261	225	565	6083	165	-117	-231	-302
15	-640	-434	160	18	21	348	1524	350	-6	-188	-236
14	-496	-264	83	-28	-30	239	473	203	16	-55	-73
13	-314	-23	47	-7	0	151	-3	106	22	-29	-53
12	27	29	24	26	19	20	9	8	-4	-6	-25
11	30	28	29	24	24	17	13	5	0	-11	-17
10	27	30	26	27	22	21	10	9	-2	-9	-17
9	31	27	29	23	24	17	14	3	0	-12	-14
8	23	28	23	26	19	19	11	6	-4	-9	-21
7	-9	3	-2	2	-2	12	23	24	12	-13	-88
6	-83	-59	-61	-42	-28	4	35	34	11	-19	-123
5	-168	-129	-118	-78	-42	-3	36	15	-21	-8	-68
4	-218	-191	-168	-136	-110	-91	-44	-56	-31	65	-60
3	-238	-224	-216	-189	-167	-116	-79	-68	-78	103	40
2	-285	-334	-298	-283	-298	-238	-235	-60	-299	-105	57

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