FAILURE PRESSURE INVESTIGATION OF PWR REACTOR COOLANT PIPE

Namgung Ihn\textsuperscript{1}, Nguyen Hoang Giang\textsuperscript{2}

\textsuperscript{1} Professor, KEPCO International Nuclear Graduate School (KINGS), Republic of Korea.
\textsuperscript{2} Graduate student, KEPCO International Nuclear Graduate School (KINGS), Republic of Korea. He is now with National Research Institute of Mechanical Engineering, Viet Nam.

ABSTRACT

In the reactor coolant primary loop of a nuclear power plant (NPP), overpressure protection system keeps pressure in the loop within 110\% design pressure. But if the system did not work properly, pressure in the loop could rise very high in short time. It would be disastrous if the piping of the loop burst, since radioactive material would release. It is customary to estimate the probability of rupture of primary pressure boundary based on fracture mechanics. In this study, such detailed fracture mechanics failure analysis with postulated initial notch condition is not carried out. Instead, comparative study of primary coolant pipe of different reactor types is carried out based on gross plastic analysis to realistically assess the maximum pressure primary system can sustain.

In this paper, burst pressures of three major reactor coolant piping (APR1400, VVER1000, and AP1000) are investigated based on non-linear FEA method. For the analysis axisymmetric models is developed to estimate burst pressure. The FEM results are compared with some existing burst pressure predictive formulae to evaluate accuracy of the prediction. In the analysis, the internal pressures are increased until stress across the entire thickness of piping reach the ultimate tensile stress. The value of pressure at that point is assumed as burst pressure.

The results from ANSYS software shows that outlet piping of VVER1000 can withstand up to the burst pressure of 161.1Mpa, while that for AP1000 is 87.92Mpa, and that of outlet piping of APR1400 is 97.16Mpa. Burst pressures using empirical formulae also give similar trend as FEM results.

INTRODUCTION

After Fukushima accident, safety of NPP is of utmost concern. One area of such concern is burst pressure assessment. In the design of Reactor Coolant System, it customarily follows ASME design rules. Hence an estimate of pressure at which system burst would not assessed in reasonable precision. The burst pressure estimate is usually regarded as beyond design basis accident simulation and provide scenario of accident progression at initial stage. The knowledge and data on burst pressure aid in emergency preparedness and also give idea on where is the weak point.

The burst pressure estimation screen out weak point in the system and quantifies the design margin to actual failure. This knowledge is useful in optimizing the system design. The designer can make component have same level of safety margin or direct to some certain component that fail earlier so that the accident progression is directed to certain scenario. This can be very useful in that reactor vessel and steam generator be designed with more margin so that fuel is submerged in coolant and radioactive material does not leak to secondary side.

Burst pressure of pressure boundary components has been investigated by theoretical, empirical methods as well as FEA methods. A comprehensive review on theoretical formulation of burst pressure prediction model as well as comparison with test data was given by Christopher, et al., Law and Bowie (2007) and
Zhu and Brian (2012). In this paper, burst pressure of the PWR primary coolant system main pipes of VVER1000, AP1400, and APR1400 were investigated and the results are compared.

**VVER1000 REACTOR COOLANT SYSTEM AND MAIN PIPE**

VVER is a pressurized water reactor developed by Rosatom Corporation, Russia. In this study VVER1000 model V320 RCS are referred to. The reactor delivers about 3000 MW of thermal power, and give output of 1000 MW electricity, from DOE (2002). The VVER reactor coolant system consist of a RV with four heat transfer loops, each of loop includes a SG, a reactor coolant pump (RCP), a single outlet pipe (hot leg pipe), and an inlet pipe (cold leg pipe).

In each loop, the outlet pipe connects RV outlet nozzle with SG inlet collector, suction pipe connects the SG outlet and RCP inlet nozzle, and inlet pipe connects between RCP outlet nozzle and RPV inlet nozzle. Four loops are installed at the same level. The angle between Loop 1 and Loop 2 is 55 degrees, and the angle between Loop 2 and Loop 3 is 125 degrees. Group of Loop 1 and 3 with group of Loop 2 and 4 are diagonally opposite to each other.

VVER1000 RCS piping comprises for circulation loop, each loop has three pipe sections. The section between PWR outlet nozzle and the SG inlet collector is hot leg pipe. The section between the SG outlet collector and inlet (intake) nozzle of the RCP set is suction leg pipe. The section between outlet nozzle of RCP set and the PWR inlet nozzle is cold leg pipe. The dimension of the internal diameter is 850 mm and nominal thickness of 140 mm. The material is used in RCS piping is steel 10GN2MFA (10Н2МФА).

Figure 1. VVER1000 reactor coolant system ([http://www.gidropress.podolsk.ru](http://www.gidropress.podolsk.ru))
AP1000 REACTOR COOLANT SYSTEM AND MAIN PIPE

AP1000 is a pressurized water reactor designed by Westinghouse Electric Company, United of States. The reactor produces a net output over 3400 MW thermal, and nominal electrical output of 1110 MW, from US NRC (2011). The AP1000 RCS consists of two heat transfer circuits. Each of circuit includes a SG, two RCPs, and a single hot leg pipe and two cold leg pipes for circulating of reactor coolant material. In addition, the system includes the pressurizer, interconnecting piping, valves, and the instrumentation for operational control and safeguards actuation. The figure 1.2 below shows arrangement of the AP1000 RCS.

Each loop of AP1000 RCS piping includes those sections of hog leg pipe and cold leg pipes interconnecting the RV, SGs, and RCPs. There are three section of pipe in each heat transfer loop: one 31 inch (787.4 mm) inner diameter pipe between RV outlet nozzle and SG inlet nozzle; two 22 inch (558.8 mm) inner diameter pipes from the RCP discharge nozzle to the RV inlet nozzle. RCS piping is fabricated of austenitic stainless steel SA 376 TP304, and fabricated according to ASME code, section III, class 1 requirement.

Figure 1. AP1000 reactor coolant system (www.decodedscience.com)
APR1400 REACTOR COOLANT SYSTEM AND MAIN PIPE

APR1400 is an advanced pressurized nuclear reactor, design by the Korea Electric Power Corporation, developed from OPR1000 design. The APR1400 reactor has a thermal power capacity of 4000 MW, produces 1400 MW gross electric power, from KHNP (2005). The RCS includes a RV with two coolant loops. The major component of a loop includes one GS, two RCPs, a pressurizer and associates piping. All components above are located inside the containment building. The arrangement of the RCS is shown in the Figure 3 below.

Each of the two transfer loops of APR1400 RCS piping contains five sections of pipe, one 42 inch (1066.8 mm) inner diameter pipe between the RV outlet nozzle and SG inlet nozzle, two 30 inch (762 mm) internal diameter pipes from SG’s two outlet nozzles to the RCPs suction nozzle, and two 30 inch (762 mm) inner diameter from pumps discharge nozzle to the RV inlet nozzles. These pipes are referred to as the hot leg, the suction legs, and the cold legs, respectively. The pipes are made of steel SA 516 Grade 70.

Figure 2. APR1400 reactor coolant system (www.asiae.co.kr)
BURST PRESSURE FORMULATION FOR THICK SHELL

When thickness of the vessel is relatively large, the variation in the stresses from inner surface to the outer surface becomes appreciable. For thick shell cylinder, \( \sigma_h \) is hoop stress and \( \sigma_r \) is radial stress. The stress in this thick shell can be shown as eq (1), from Harvey (1987), pp 58.

\[
\sigma_h - \sigma_r - r \frac{d\sigma_r}{dr} = 0 \quad \text{or} \quad \frac{\sigma_h - \sigma_r}{r} = \frac{d\sigma_r}{dr}
\]  

(1)

Note that \( \sigma_h \) and \( \sigma_r \) are maximum and minimum principal stresses respectively, thus by applying Tresca’s yield criteria we can state when the maximum shear stress reaches yield stress, yielding occurs at the inside vessel surface.

\[
\tau_{\text{max}} = \tau_y = \frac{\sigma_h - \sigma_r}{2}
\]  

(2)

As the pressure is continued to increase, plastic deformation penetrates farther into the wall of the vessel until reaches the outer surface with an assumption that the material is perfectly plastic and shear stress is constant through the walled thickness. Thus every point in the walled thickness of the vessel is in the plastic state and reaches the shear stress value as in the eq. (2). Substituting eq. (2) to eq. (1) gives:

\[
2\tau_y = \frac{d\sigma_r}{dr}
\]  

(3)

Integration of both sides of the (Eq.4) give:

\[
\sigma_r = 2\tau_y \ln r + C
\]  

(4)

From the condition that at the outer surface of the vessel, \( r = b \), the radical stress become zero. Applying boundary condition, the integration constant is obtained as \( C = -2\tau_y \ln b \). Thus, 

\[
\sigma_r = 2\tau_y \ln \frac{r}{b}
\]

At inner surface of the vessel, \( r = a \), the radial stress equals to the internal pressure, hence,

\[
p = -\sigma_r.a = -2\tau_y \ln \frac{a}{b} \quad \text{or} \quad p = 2\tau_y \ln \frac{b}{a}
\]  

(5)

The pressure expressed in eq. (5) is the required value of pressure to bring entire wall of the vessel into state of plastic flow. Assumption is made that upon reaching the burst pressure, the shearing stress are uniform over the entire thickness and equal to the ultimate shearing strength of the material. The burst pressure is determined as,

\[
p_b = 2\tau_u \ln \frac{b}{a}
\]  

(6)

The value \( \tau_u \) is difficult to obtain, so by applying the Tresca’s criterion for material at critical point, \( 2\tau_u \) equal to the ultimate tensile strength of material \( \sigma_u \), and the burst pressure is determined by the eq. (6).

\[
p_b = \sigma_u \frac{\partial a}{\partial i}
\]  

(7)

The eq. (7) is known as Turner equation, Harvey (1987), pp72, based on Tresca’s yield criteria.

Svensson (1958) presented burst pressure prediction formula for material with strain hardening case based on von Mises criteria.

\[
p_b = \sigma_u \left[ \frac{0.25}{n+0.2273} \left( \frac{\varepsilon}{n} \right)^n \right] \ln \frac{\partial a}{\partial i}
\]  

In eq. (8), \( n \) is material’s strain hardening exponent. Faupel, Zhu and Brian (2012) and Faupel and Fisher, (1981) , carried out experiment and presented the burst pressure prediction formula incorporating yield and ultimate tensile strength based on von Mises criteria.

\[
p_b = \frac{2}{\sqrt{3}} \sigma_y \left( 2 - \frac{\sigma_y}{\sigma_u} \right) \ln \frac{\partial a}{\partial i}
\]  

(9)

Bailey and Nadai developed burst pressure formula based on maximum shear stress plasticity relations.

\[
p_b = \frac{\sigma_u}{2n} \left[ 1 - \frac{1}{\left( \frac{\partial a}{\partial i} \right)^n} \right]
\]  

(10)
where $n$ is material’s strain hardening exponent. Soderberg (1958) proposed burst pressure prediction formula based upon assumption of uniform stress distribution throughout the wall by considering the average stress value and failure as a function of the significant stress or octahedral shear stress.

$$ p_b = \frac{4}{\sqrt[3]{2}} \sigma_u \left( \frac{k - 1}{k + \frac{1}{2}} \right) $$

(12)

In the 1962 ed. of the ASME Boiler code section VIII gives the equation for allowable maximum pressure for pressure vessel. The estimation of burst pressure is not included in the current ASME code.

$$ p_b = \sigma_u \left( \frac{k - 1}{0.6k + 0.4} \right) $$

for $k \leq 1.5$

(13)

These equations given above are used in comparison with FEM result in this study.

**BURST PRESSURE PREDICTION OF NPP PRIMARY SYSTEM BY FEA**

In the FEA analyses, reactor vessel, steam generator, RC pump, pressurizer and main pipes, etc. are subjected to internal pressure. Assumptions are made that external pressure is negligible compare to internal pressure. The failure pressures are predicted by incrementally increasing the value of internal pressure from design pressure, at each increment in the value of internal pressure, the maximum stress is determined and compared with critical strength of the materials. Yield pressure is defined as the pressure value at which the material starts to yield, and burst pressure is defined as the pressure value at which entire wall thickness of vessel reaches the magnitude of ultimate tensile strength. The increase in pressure was controlled so not to exceed 0.1 MPa in the plastic region and the typical step size in pressure before the failure was 0.01 MPa to get more accuracy results. The FEA analysis to estimate burst pressure of reactor main pipe is performed using ANSYS.

**MATERIAL PROPERTIES AND PRIMARY PIPE GEOMETRIES**

VVER1000 RCS piping includes three sections, hot leg pipe, loop-closure pipe, and cold leg pipe. The main pipes have same inner diameter of 850 mm and nominal thickness of 140 mm. The material used in the RCS piping is 10GN2MFA steel. At normal operating condition, the temperature at hot leg pipe is 318°C, and that for cold leg pipe is 287°C. The burst pressure evaluation was done based on material properties at temperature of 350°C. This will give slightly conservative result since at higher temperature the yield and tensile stress is lower. The table 1 below shows material properties of 10GN2MFA steel for analysis.

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>$\nu$ (Poisson’s ratio)</th>
<th>$\rho$ (density, kg/m$^3$)</th>
<th>$E$ (modulus of elasticity, GPa)</th>
<th>$\sigma_y$ (yield strength, MPa)</th>
<th>$\sigma_u$ (ultimate strength, MPa)</th>
<th>$n = \sigma_y / \sigma_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°C</td>
<td>0.3</td>
<td>7860</td>
<td>200</td>
<td>345</td>
<td>540</td>
<td>0.64</td>
</tr>
<tr>
<td>350°C</td>
<td>0.3</td>
<td>7778</td>
<td>181</td>
<td>295</td>
<td>490</td>
<td>0.6</td>
</tr>
</tbody>
</table>

AP1000 RCS piping includes three sections, i.e. hot leg pipe and two cold leg pipes. Hot leg pipe has inner diameter of 31 inch (787.4 mm), and nominal thickness of 3.25 inch (82.6 mm). Cold leg pipes have inner diameter of 22 inch (558.8 mm) and nominal thickness of 2.56 inch (65 mm). AP1000 RCS piping is fabricated of SA-376 TP304 austenitic stainless steel. The normal operation temperature of hot leg pipes is 610°F (321°C) and cold leg pipes is 535°F (279.44°C). The burst pressure analysis was performed based on design temperature of the RCS (650°F). The table 2 below shows some main material properties of SA-376 TP304 steels at 70°F (21°C) and 650°F (343°C).

<table>
<thead>
<tr>
<th>Temp. (°F)</th>
<th>$\nu$ (Poisson’s ratio)</th>
<th>$\rho$ (density, kg/m$^3$)</th>
<th>$E$ (modulus of elasticity, GPa)</th>
<th>$\sigma_y$ (yield strength, MPa)</th>
<th>$\sigma_u$ (ultimate strength, MPa)</th>
<th>$n = \sigma_y / \sigma_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>70°F</td>
<td>0.3</td>
<td>7860</td>
<td>200</td>
<td>345</td>
<td>540</td>
<td>0.64</td>
</tr>
<tr>
<td>650°F</td>
<td>0.3</td>
<td>7778</td>
<td>181</td>
<td>295</td>
<td>490</td>
<td>0.6</td>
</tr>
</tbody>
</table>
APR1400 RCS piping consists of 2+4 loop design in which 2 hot leg pipes, 4 cold leg pipes and 4 loop closure pipes. The hot leg pipe inner diameter is 42 inch (1066.8 mm) and nominal thickness of 4 inch (101.6 mm). The loop closure pipe and cold leg pipes inner diameter is 30 inch (762 mm) and nominal thickness of 3 inch (76.2 mm). The APR1400 RCS piping is fabricated of SA-516 Grade 70 austenitic stainless steel. The normal operation temperature of hot leg pipes is 615°F (323.9°C) and cold leg pipes is 555°F (290°C). Table 3 shows material properties of SA-516 at 70°F (21°C) and 650°F (343°C).

<table>
<thead>
<tr>
<th>Temp.</th>
<th>ν (Poisson’s ratio)</th>
<th>ρ (density, kg/m³)</th>
<th>E (modulus of elasticity, GPa)</th>
<th>σᵧ (yield strength, MPa)</th>
<th>σᵤ (ultimate strength, MPa)</th>
<th>n = σᵧ/σᵤ</th>
</tr>
</thead>
<tbody>
<tr>
<td>70°F (21°C)</td>
<td>0.30</td>
<td>7850</td>
<td>202 (29400)</td>
<td>262 (38.0)</td>
<td>482.6 (70)</td>
<td>0.54</td>
</tr>
<tr>
<td>650°F (343.3°C)</td>
<td>0.30</td>
<td>7850</td>
<td>182 (26500)</td>
<td>194 (28.2)</td>
<td>482.6 (70)</td>
<td>0.4</td>
</tr>
</tbody>
</table>

FEA MODEL AND ANALYSIS RESULT

The burst pressure assessment using FEA methods has been investigated widely, Nidhi, et al, (2013), Xue, Widera, and Sang, (2008), and Zhu and Leis, (2007). Nidhi reviewed various types of methods, formulae and theories for burst pressure calculation. Xue demonstrated accurate calculation of the burst pressure using FEM method employing nonlinear material behaviour and geometric nonlinearity. Zhu developed burst pressure prediction based on the average shear stress yield theory and proposed criteria of burst pressure, and made comparisons between experimental data and the results obtained by FEM method.

In order to simplify the RCS primary pipe FEA analysis, straight section and elbow sections are modelled separately. Fig. 4 shows a typical model of straight section and various elbow section of APR1400 primary pipes. Also symmetry of geometry was taken accounted to reduce the model size. For VVER-1000

Figure 4. FEA model of primary pipe sections of APR1400
RCS primary pipes, the I.D. and thickness of pipe are same for hot leg, cold leg and loop closure pipe. Therefore the burst pressure at straight sections is the same. In case of AP1000, there is no loop closure pipe, since RC pump is directly connected to the SG. Also the radius of elbow is much larger than APR1400 RCS primary pipe in order to reduce local stress concentration. The symmetry plane is set to frictionless support and one end of the beam was set for fixed and the other end is set to free. The analyses were performed with large-deflection non-linear option with bilinear plasticity. Tables 4 through 6 are summary of analysis results for burst pressures for VVER-1000, AP1000 and APR1400 RCS pipes.

Table 4, Burst pressure estimation of VVER-1000 RCS pipe

<table>
<thead>
<tr>
<th>Location</th>
<th>Yield pressure at elbow region</th>
<th>Yield pressure at straight region</th>
<th>Burst pressure at elbow region</th>
<th>Burst pressure at straight region</th>
<th>Design pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot leg and cold leg pipes</td>
<td>51.0 MPa</td>
<td>73.1 MPa</td>
<td>138.72 MPa</td>
<td>160.1 MPa</td>
<td>15.7 MPa</td>
</tr>
<tr>
<td>Loop closure pipe</td>
<td>51.0 MPa</td>
<td>73.1 MPa</td>
<td>136.5 MPa</td>
<td>160.1 MPa</td>
<td>15.7 MPa</td>
</tr>
</tbody>
</table>

Table 5, Burst pressure estimation of AP1000 RCS pipe

<table>
<thead>
<tr>
<th>Location</th>
<th>Yield pressure at elbow region</th>
<th>Yield pressure at straight region</th>
<th>Burst pressure at elbow region</th>
<th>Burst pressure at straight region</th>
<th>Design pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot leg pipe</td>
<td>20.5 Mpa</td>
<td>25.8 Mpa</td>
<td>79.80 Mpa</td>
<td>87.70 Mpa</td>
<td>17.13 MPa</td>
</tr>
<tr>
<td>Cold leg pipe</td>
<td>20.4 Mpa</td>
<td>26.9 Mpa</td>
<td>91.95 Mpa</td>
<td>96.50 Mpa</td>
<td>17.13 MPa</td>
</tr>
</tbody>
</table>

Table 6, Burst pressure estimation of APR1400 RCS pipe

<table>
<thead>
<tr>
<th>Location</th>
<th>Yield pressure at elbow region</th>
<th>Yield pressure at straight region</th>
<th>Burst pressure at elbow region</th>
<th>Burst pressure at straight region</th>
<th>Design pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot leg pipe</td>
<td>22.0 MPa</td>
<td>31.8 MPa</td>
<td>91.83 MPa</td>
<td>97.30 MPa</td>
<td>15.51 MPa</td>
</tr>
<tr>
<td>Cold leg pipe</td>
<td>22.6 MPa</td>
<td>33.0 MPa</td>
<td>92.00 MPa</td>
<td>101.5 MPa</td>
<td>15.51 MPa</td>
</tr>
<tr>
<td>Loop closure pipe</td>
<td>21.7 MPa</td>
<td>33.0 MPa</td>
<td>82.2 MPa</td>
<td>101.5 MPa</td>
<td>15.51 MPa</td>
</tr>
</tbody>
</table>

**BURST PRESSURE ESTIMATION BY FORMULA**

Formulæ (8) to (13) for burst pressure estimation are for cylindrical shell sections. Thus the formulæ are not applicable to the estimation of burst pressure of elbow section. Since the lack of more detailed material properties of VVER-1000, AP1000 and APR1400 prevented to obtaining strain hardening exponents for each material. Hence, the following strain harden exponent relationship, from Brabin (2011), is used in the evaluation of burst pressure.

\[ n = 0.224 \left( \frac{\sigma_u}{\sigma_y} - 1 \right)^{0.604} \]  \hspace{1cm} (14)

In eq. (14) the ultimate stress, \( \sigma_u \), and yield stress, \( \sigma_y \), are specified for room temperature and temperature beyond design temperature. Therefore linear interpolation is used to get ultimate stress and yield stress at design temperature. The value of strain hardening exponents obtained using eq. (14) are given in Table 7 and within the range of 0.1 to 0.4, hence it accord with general material behaviour.

Table 7 shows the summary of the burst pressure of RCS pipe for VVER-1000, AP1000, and APR1400 obtained from different formulation. Faupel’s formula give most conservative result while Soderberg’s formula gives highest value of burst pressure. This is attributed to the formulation as well as experimental materials they use affected the formula.
Table 7, Burst pressure estimation of Primary Pipe by theoretical formulae

<table>
<thead>
<tr>
<th>RCS Pipe</th>
<th>Burst pressure by FEM analysis ( (p_b) )</th>
<th>Design pressure ( (p_d) )</th>
<th>( p_d/p_b ) (ratio of design pressure to burst pressure)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VVER-1000</td>
<td>136.5 MPa</td>
<td>15.7 MPa</td>
<td>0.115</td>
</tr>
<tr>
<td>AP1000</td>
<td>79.80 MPa</td>
<td>17.13 MPa</td>
<td>0.215</td>
</tr>
<tr>
<td>APR1400</td>
<td>82.2 MPa</td>
<td>15.51 MPa</td>
<td>0.189</td>
</tr>
</tbody>
</table>

CONCLUSIONS

As the safety of NPP is increasing concern, the behaviour of reactor and primary system during severe accident is becomes important. The structural loading on NPP system at such accident is beyond anticipated and exceeds design limits. The concern is what component fails first so the accident failure scenario can be predicted with reasonable basis. The burst pressure calculation is to get an idea of how much system can sustain and what component fails first when safety relief value wouldn’t work as designed during severe accident such as core melting case. In this study, burst pressure calculation was performed on primary pipe of VVER-1000, AP1000 and APR1400 reactor system.

Comparing the FEM analysis and theoretical evaluation from Tables 7 and 8, Nadai-Bailey’s formula gives comparable results to FEM analysis. Soderberg’s formula over estimates the burst pressure most while Faupel’s formula under-estimates.

From Tables 4, 5, and 6, burst pressure at elbow region is lower than straight region. This is due to higher stress inside of elbow and in FEM simulation the yield stress reaches first inside and propagates through the thickness. The summary of lowest burst pressure is shown in Table 8. Comparing to the design pressure, AP1000’s burst pressure is less than 5 times the design pressure, while that for VVER-1000 is more than 8 times the design pressure.

Table 8, Summary of burst pressure estimation of RCS pipes

In this study, failure stresses of components in three reactor coolant systems pipes are investigated. The results show that in case there are certainly accidents happened compounded with the overpressure protection systems failure to keep internal pressure is within 110% of design pressure, those reactor coolant system pipes still can withstand at least for the internal pressure of up to 465% of design pressure (in case of AP1000), 870% of design pressure for VVER-1000 and 530% of design pressure for APR1400 RCS pipe.
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