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1. PURPOSE

The objective of this calculation is to determine areas over the drip shield (DS) top plate and sidewalls where the residual stress values exceed 50% of Ti-7 yield strength (see Assumption 3.17). These areas will also be referred to as the damaged areas throughout this document. The scope of this document is limited to reporting the calculation results in terms of the damaged areas based on a chosen set of stress components. This calculation is intended for use in support of the preliminary design activities for the license application design of the DS. This calculation is associated with the DS design and was performed by the Waste Package and Components. AP-3.12Q, *Design Calculations and Analyses* (Ref. 15) is used to perform the calculation and develop the document. The DS is classified as a safety category item (Ref. 1, p. A-5). Therefore, this calculation is subject to the *Quality Assurance Requirements and Description* (Ref. 8). The information provided by the sketches attached to this calculation is that of the potential design of the type of DS considered in this calculation and provides the potential dimensions and materials for the DS design.

2. METHOD

The finite element (FE) calculation was performed by using the commercially available LS-DYNA Version (V)960 (Software Tracking Number [STN] 10300-960.1106-00, Ref. 7) FE code. The results of this calculation were evaluated using residual first principal stress. Subsequent analysis of areas determined by residual stresses have been reported in the results section of this document. The finite element mesh adequacy was determined based on the maximum stress intensity and maximum first principal stress.

The current work processes and procedures for the control of the electronic management of data for this activity were conducted in accordance with AP-3.13Q, *Design Control* (Section 5.1.2) (Ref. 3).

3. ASSUMPTIONS

In the course of developing this document, the following assumptions are made regarding the structural calculation.

3.1 Temperature-dependent Poisson's ratio is not available for Ti-7 (titanium Grade 7) and Ti-24 (titanium Grade 24). Therefore, the room temperature (RT) Poisson's ratio is assumed for these materials. The impact of using Poisson's ratio at room temperature is anticipated to be small. The rationale for this assumption is twofold: for the subject materials, this property does not change significantly at the temperature of interest in this calculation; secondly, the material property in question does not have dominant impact on the calculation results. This assumption is used in Section 5.1.

3.2 The temperature-dependent material properties are not available for TSw2 (Topopah Spring Welded-Lithophysal Poor) rock except at RT. The corresponding RT material properties are assumed for this material. The impact of using RT material properties is anticipated to be small. The rationale for this assumption is that the material properties of the rock do not have dominant impact on the calculation results. The likely exception is the yield strength of the rock which decreases with the increase of temperature. Thus, the representation of the rock as an elastic-ideally-plastic solid with RT yield strength is conservative. This assumption is used in Section 5.1.

3.3 Some of the rate-dependent material properties are not available for materials subjected to dynamic loads. The material properties obtained under the static loading conditions are assumed for all materials. The impact of using material properties obtained under static loading conditions is anticipated to be small. The rationale for this assumption is that the mechanical properties of subject materials do not significantly change at the peak strain rates that occur during the rock fall (maximum strain rate being approximately 40 s^{-1} as indicated by maximum slope [0.2 / 0.005 s] in Figure II-3). A possible exception is TSw2 rock, but since the rock is represented as an elastic-plastic solid, the same justification is valid for the relevant rock properties as well. This assumption is used in Section 5.1.

3.4 The friction coefficient for contact among Alloy 22 (DS base plate material, which is excluded from FE representation, see Assumption 3.14) and stainless steel is not available in literature. It is, therefore, assumed that the dynamic (sliding) friction coefficient for this contact is 0.5. The rationale for this conservative assumption is that this friction coefficient represents a mean value for most dry nickel-on-steel contacts (see Ref. 19 [Table 3.2.1, p. 3-26]), nickel being the dominant component in Alloy 22 (Ref. 2, Section II, Part B, SB-575, Table 1). This assumption is used in Section 5.4.

3.5 The friction coefficient for contacts occurring between the rock and Ti-7 or invert and Alloy 22 is not available in literature. It is, therefore, assumed that the dynamic (sliding) friction coefficient for this contact is 0.5. The rationale for this assumption is that this friction coefficient represents a reasonable estimate based on available information for metal-on-stone contacts (see Ref. 20 [Table 8.1, p. 306]). This parameter does not have significant effect on the results since the relative surface-to-surface movement of these components is not a significant determining factor in the amount of deformation during impact. This assumption is used in Sections 5.4.

3.6 The variation of functional friction coefficient between the static and dynamic value as a function of relative velocity of the surfaces in contact is not available in literature for the materials used in this calculation. Therefore, the effect of relative velocity of the surfaces in contact is neglected in these calculations by assuming that the functional friction coefficient and the static friction coefficient are both equal to the dynamic friction coefficient. The impact of this assumption on the results presented in this document is anticipated to be negligible. The rationale for this conservative assumption is that it provides a bounding set of results by minimizing the friction coefficient within the given FE-analysis framework. This assumption is used in Section 5.4.

3.7 The temperature of the DS is assumed to be 150 °C. The rationale for this assumption is that this temperature is conservative for most of the regulatory period for high-temperature operating modes and strictly conservative for low-temperature operating modes. The waste package temperature remains below 150 °C for the 97% of the regulatory time period, 10,000 years (see Ref. 23, Figure 6-3) and the drip shield temperature is less than the waste package temperature. This assumption is used in Section 5.1.

3.8 The previous version of this document used an unconfined compressive strength value of 290 MPa for TSw2 rock (Ref. 32, Assumption 3.8). A recent drift degradation study revealed that a recommended value of 70 MPa can be used for compressive strength (Ref. 33, Figure V-5). In terms of the damage to the drip shield components, since using a rock compressive strength of 290 MPa is conservative when compared to 70 MPa, a new calculation is not warranted at this time for the purpose of the present document. The rationale for this assumption is that it leads to bounding set of results. This assumption is used in Sections 5.1 and 5.4.1.

3.9 The uniform strains (the strains corresponding to the uniaxial tensile strengths) of Ti-7 and Ti-24 are not available in literature. Therefore, it is assumed that the uniform strain is equal to the elongation. The rationale for this assumption is that a small change in tangent modulus does not significantly affect the results of this calculation. This assumption is used in Section 5.1.2.

3.10 The thickness of the Ti-7 and T-24 plates are reduced by 2 mm (DTN: MO0306SPAGLCDS.001 [Ref. 25], file name: 5-year CR-Data.pdf). The rationale for this assumption is that the maximum general corrosion of titanium in 10,000 years is conservatively determined using the corrosion rate for 100th percentile value for both sides of the titanium plate (see Ref. 30 and Ref. 24, Section 6.3.3.2). Furthermore, Reference 24, page 12 states that Ti-16 was used as an analog of Ti-7 for the corrosion tests due to its compositional similarity to Ti-7. This assumption is used in Section 5.4.

3.11 The rock shape is assumed to be a rectangular prism. The rationale for this assumption is: the rock block data shows that some of the rock blocks are essentially rectangular prism. A finite element representation of the rock with an inclined rectangular prism provides a conservative approach from the point of view that the rock center of gravity is located directly above the point of impact, transferring the maximum linear momentum to the DS. The sharp edge of the prism also results in maximum strain on the DS plate. The vertex coordinates of the prism are obtained from Reference 26 (Block Geometry Information.doc) in order to calculate the enveloping dimensions. This assumption is used in Section 5.3.

3.12 Five different rock blocks from 10^{-6} ground motion and one rock block from 10^{-7} ground motion data have been used in these calculations. 10^{-6} ground motion rock blocks are identified as follows (see Ref. 22 [1e-6 3DEC non-lith analysis summary.xls], and Ref. 28 [Rock Block Properties.doc]):
14.5 metric ton (MT) rock: line #194, kinetic energy = 163083 J, vertical velocity = 4.69 m/s, lateral velocity = 0.656 m/s
3.3 MT rock: line #13, kinetic energy = 24712 J, vertical velocity = 3.75 m/s,

lateral velocity = 0.0824 m/s
0.15 MT rock: line #95, kinetic energy = 902 J, vertical velocity = 3.09 m/s,
lateral velocity = 0.955 m/s
0.11 MT rock: line #270, kinetic energy = 42 J, vertical velocity = 0.202 m/s,
lateral velocity = 0.383 m/s
0.25 MT rock: line #233, kinetic energy ~ 0 J, vertical velocity = 0.0137 m/s,
lateral velocity = 0.0103 m/s

10^{-7} ground motion rock block is identified as follows (see Ref. 26):
11.5 MT rock: line #298, kinetic energy = 348174 J, vertical velocity = 7.77 m/s,
lateral velocity = 0.295 m/s

These rock blocks are assumed to reperesent a range of rock mass and velocities that may occur during the 10,000-year regulatory period. The basis for this assumption is that the subject rock block data were obtained for 10^{-6} and 10^{-7} ground motion analyses (see Ref. 22 [1e-6 3DEC non-lith analysis summary.xls], Ref. 26 [post-closure 1e-7 gm analysis summary.xls], and Ref. 28 [Rock Block Properties.doc]). This assumption is used in Sections 5.2, 5.3, and 5.5.2.

3.13 The drip shield side-walls are assumed to be unconstrained in lateral direction during the 10,000-year regulatory period. The rationale for this assumption is that the gantry rail is made of steel sets (Ref. 27, Attachment A-1), which are not anticipated to remain intact (eventually corrode away) during the 10,000-year regulatory period. This assumption is used in Section 5.4.

3.14 Alloy 22 base is excluded from the FE representation for simplicity. The rationale for this assumption is that the effect of a thin plate at the bottom of the long side wall is negligibly small during rock fall. This assumption is used in Section 5.4.

3.15 The modulus of elasticity and Poisson's ratio of the TSw2 are characterized by significant scatter of data (see Ref. 11, Tables 3 and 4, respectively). For the purpose of the present calculation modulus of elasticity is assumed to be 33 *GPa*, and Poisson's ratio 0.21. The rationale for this assumption is that these values agree well with typical values of said properties for most rocks of interest (see Ref. 11, Tables 3 and 4). This assumption is used in Section 5.1.

3.16 The density of the TSw2 is assumed to be $2370\,kg/m^3$. The rationale for this assumption is that this value agrees well with all Topopah Spring Welded rocks in Reference 10 (Table 2). It should be noted though that this assumption has no effect on the calculation results since the important input parameter is mass of the rock regardless of the density. This assumption is used in Section 5.1.

3.17 The residual stress threshold is assumed to be a constant value, equal to 50% of the yield strength of titanium Grade 7. The basis for this assumption is the data provided in Reference 29 [Seismic Failure Criteria.doc]. This calculation will determine areas over the drip shield (DS) top plate and side-walls where the residual stress values exceed 50% of Ti-7 yield strength. This assumption is used in Section 1.

4. USE OF COMPUTER SOFTWARE

The qualified FE analysis computer code used for this calculation is Livermore Software Technology Corporation (LSTC) LS-DYNA V960 (Ref. 7). LS-DYNA V960 was obtained from Software Configuration Management in accordance with the appropriate procedures (Ref. 13) and is identified by STN 10300-960.1106-00. LS-DYNA V960 is appropriate for its intended use. The LS-DYNA evaluation performed for this calculation is fully within the range of the validation performed for the LS-DYNA V960 code. The calculations were executed on two HP 9000 series UNIX workstations (Operating System HP-UX 11.0) identified with the YMP property tag numbers 117162 and 150691, located in Las Vegas, Nevada. This application has been validated by the test cases in Reference 31, Sections 4 and 5. Access to the code is granted by Software Configuration Management in accordance with the appropriate procedures.

The input files (identified by .k and .inc file extensions) and output files (messag) for LS-DYNA V960 are listed in Section 8, and provided in Attachment III.

The finite element mesh, which is subsequently used in the LS-DYNA solver, is developed using ANSYS V5.6.2, which is obtained from Software Configuration Management in accordance with appropriate procedures (Ref. 13), and is identified by STN 10364-5.6.2-01 (Ref. 16). ANSYS V5.6.2 is a qualified commercially available FE code and is appropriate for developing the finite element mesh used in this calculation. The calculations using ANSYS V5.6.2 software were executed on a Hewlett-Packard (HP) 9000 series UNIX workstation (Operating System HP-UX 11.0) identified with the YMP (Yucca Mountain Project) property tag number 117162, located in Las Vegas, Nevada. The ANSYS evaluation performed for this calculation is fully within the range of the validation performed for ANSYS V5.6.2 code. Access to the code is granted by Software Configuration Management in accordance with the appropriate procedures. Since ANSYS V5.6.2 is used only for mesh development purposes, a validation test case is not cited in this calculation.

The input files (identified by .inp file extension) and output files (identified by .out file extension) for ANSYS V5.6.2 are listed in Section 8, and provided in Attachment III. Note that some cases do not include these files; for these cases, LS-DYNA inputs were directly obtained from other cases that were already run using ANSYS input files.

As identified in Section 6, LSTC LS-PRE/POST Version 1.0 (Beta) is used as a post-processor for graphical representation plotting tool that is exempt in accordance with Reference 13 (Section 2.1.2).

5. CALCULATION

5.1 MATERIAL PROPERTIES

Material properties used in these calculations are listed in this section. The DS temperature is assumed to be 150 °C (Assumption 3.7). Some of the temperature-dependent and rate-dependent material properties are not available for Ti-7, Ti-24, and TSw2 rock. Therefore, RT Poisson's ratio, elongation, and modulus of elasticity obtained under the static loading conditions are used for these materials (see Assumptions 3.1 through 3.3).

Ti-7 (Titanium Grade 7) (SB-265 R52400, see Attachment I):

Modulus of elasticity = 101 GPa (14.6 * 10^6 psi) (at 149 °C = 300 °F) (Ref. 14, page 3)

Modulus of elasticity = 97 GPa (14.0 * 10^6 psi) (at 204 °C = 400 °F) (Ref. 14, page 3)

Density = 4500 - 4540 kg/m^3 (a mean value of 4520 kg/m^3 is used) (at room temperature [RT]) (Ref. 14, page 1)

Poisson's ratio = 0.32 (at RT) (Ref. 14, page 3)

Yield strength = 275 - 450 MPa (a mean value of 363 MPa is used) (at RT) (Ref. 14, page 2)

Yield strength = 138 - 152 MPa (a mean value of 145 MPa is used) (at 204 °C = 400 °F) (Ref. 14, page 2)

Tensile strength = 345 MPa (at RT) (Ref. 14, page 2)

Tensile strength = 207 - 228 MPa (a mean value of 218 MPa is used) (at 204 °C = 400 °F) (Ref. 14, page 2)

Elongation = 0.2 (at RT) (Ref. 14, page 2)

Elongation = 0.38 – 0.45 (a mean value of 0.42 is used) (at 204 °C = 400 °F) (Ref. 14, page 2)

Ti-24 (Titanium Grade 24) (SB-265 R56405; in regard to this UNS designation, note that Ti-24 has the same mechanical properties with Ti-5 since the compositions are almost identical, see Ref. 2, Section II, Part B, SB-265, Table 2) (see Attachment I) (material properties of Ti-24 given below are specified using the nominal composition, 6Al-4V):

Modulus of elasticity = 107 - 122 GPa (a mean value of 115 GPa is used) (at RT) (Ref. 21, Table 2)

Modulus of elasticity = 95 - 111 GPa (a mean value of 103 GPa is used) (at 230 °C = 450 °F) (Ref. 21, Table 2)

Density = 4430 kg/m^3 (0.16 lb/in^3) (at RT) (Ref. 5, p. 620)

Poisson's ratio = 0.34 (at RT) (Ref. 5, p. 621)

Yield strength = 910 MPa (132 ksi) (at RT) (Ref. 6, page 11)

Yield strength = 683 MPa (99 ksi) (at 204 °C = 400 °F) (Ref. 6, page 11)

Tensile strength = 1000 MPa (145 ksi) (at RT) (Ref. 6, page 11)

Tensile strength = 772 MPa (112 ksi) (at 204 °C = 400 °F) (Ref. 6, page 11)

Elongation = 0.18 (at RT) (Ref. 6, page 11)

Elongation = 0.17 (at 204 °C = 400 °F) (Ref. 6, page 11)

TSw2 Rock:

Density = 2370 *kg/m*^{3} (at RT) (Assumption 3.16)

Unconfined compressive strength = 290 MPa (at RT) (Assumption 3.8)

Poisson's ratio = 0.21 (at RT) (Assumption 3.15)

Modulus of elasticity = 33.0 *GPa* (at RT) (Assumption 3.15)

5.1.1 Calculation for Material Properties at Elevated Temperature

Some of the material properties of Ti-7 and Ti-24 are not available at $T_{max} = 150\,°C$ (see Section 5.1). They are, therefore, obtained by linear interpolation by using

$$P = P(T) = P_l + \left(\frac{T - T_l}{T_u - T_l}\right) \cdot (P_u - P_l)$$

where subscripts u and l denote the bounding values of the property (P) at the corresponding bounding temperatures (T).

Thus, for Ti-7 modulus of elasticity

$$\mathrm{E}(150\,°C) = 101 + \left(\frac{150 - 149}{204 - 149}\right) \cdot (97 - 101) = 101 \text{ GPa} \quad \text{(see Section 5.1)}$$

Ti-7 yield strength

$$Sy(150\ ^{\circ}C) = 363 + \left(\frac{150-20}{204-20}\right)\cdot(145-363) = 209\ \text{ MPa}\ \ \text{(see Section 5.1)}$$

Ti-7 tensile strength

$$Su(150\ ^{\circ}C) = 345 + \left(\frac{150-20}{204-20}\right)\cdot(218-345) = 255\ \text{ MPa}\ \ \text{(see Section 5.1)}$$

Ti-7 elongation

$$\text{Elongation}(150\ ^{\circ}C) = 0.2 + \left(\frac{150-20}{204-20}\right)\cdot(0.42-0.2) = 0.36\ \ \text{(see Section 5.1)}$$

Ti-24 modulus of elasticity

$$E(150\ ^{\circ}C) = 115 + \left(\frac{150-20}{230-20}\right)\cdot(103-115) = 108\ \text{ GPa}\ \ \text{(see Section 5.1)}$$

Ti-24 yield strength

$$Sy(150\ ^{\circ}C) = 910 + \left(\frac{150-20}{204-20}\right)\cdot(683-910) = 750\ \text{ MPa}\ \ \text{(see Section 5.1)}$$

Ti-24 tensile strength

$$Su(150\ ^{\circ}C) = 1000 + \left(\frac{150-20}{204-20}\right)\cdot(772-1000) = 839\ \text{ MPa}\ \ \text{(see Section 5.1)}$$

Ti-24 elongation

$$\text{Elongation}(150\ ^{\circ}C) = 0.18 + \left(\frac{150-20}{204-20}\right)\cdot(0.17-0.18) = 0.17\ \ \text{(see Section 5.1)}$$

5.1.2 Calculations for True Measures of Ductility

The material properties in Section 5.1 refer to engineering stress and strain definitions: $s = P/A_0$ and $e = L/L_0 - 1$ (see Ref. 4, Chapter 9), where P stands for the force applied during a static tensile test, L is the length of the deformed specimen, and L_0 and A_0 are the original length and cross-sectional area of the specimen, respectively. The engineering stress-strain curve does not give a true indication of the deformation characteristics of a material during plastic deformation since it is based entirely on the original dimensions of the specimen. In addition, ductile metal that is pulled in tension becomes unstable and necks down during the course of the test. Hence, LS-DYNA V960 FE code requires input in terms of true stress and strain definitions: $\sigma = P/A$ and $\varepsilon = \ln(L/L_0)$ (see Ref. 4, Chapter 9).

The relationships between the true stress and strain definitions and the engineering stress and strain definitions, $\sigma = s \cdot (1+e)$ and $\varepsilon = \ln(1+e)$, can be readily derived based on constancy of volume ($A_0 \cdot L_0 = A \cdot L$) and strain homogeneity during plastic deformation (see Ref. 4, Chapter 9). These expressions are applicable only in the hardening region of the stress-strain curve that is limited by the onset of necking.

In absence of data on the uniform strain in available literature, the uniform strain is estimated based on the material elongation (strain corresponding to rupture of the tensile specimen) (see Assumption 3.9).

The following parameters are used in the subsequent calculations:

$s_y \approx \sigma_y$ = yield strength
s_u = engineering tensile strength
σ_u = true tensile strength
$e_y \approx \varepsilon_y$ = strain corresponding to yield strength
e_u = engineering strain corresponding to tensile strength (engineering uniform strain)
ε_u = true strain corresponding to tensile strength (true uniform strain)

For Ti-7, the true measures of ductility are

$$\varepsilon_u = \ln(1+e_u) = \ln(1+0.36) = 0.31 \quad \text{(at 150 °C) (see Section 5.1.1)}$$
$$\sigma_u = s_u \cdot (1+e_u) = 255 \cdot (1+0.36) = 347 \text{ MPa} \quad \text{(at 150 °C) (see Section 5.1.1)}$$

For Ti-24

$$\varepsilon_u = \ln(1+e_u) = \ln(1+0.17) = 0.16 \quad \text{(at 150 °C) (see Section 5.1.1)}$$
$$\sigma_u = s_u \cdot (1+e_u) = 839 \cdot (1+0.17) = 982 \text{ MPa} \quad \text{(at 150 °C) (see Section 5.1.1)}$$

5.1.3 Calculations for Tangent Moduli

As previously discussed, the results of this simulation are required to include elastic and plastic deformations for Ti-7 and Ti-24. When the materials are driven into the plastic range, the slope of the stress-strain curve continuously changes. A ductile failure is preceded by a protracted regime of hardening and substantial accumulation of inelastic strains. Thus, a simplification for stress-strain curve is needed to incorporate plasticity into the FE analysis. A standard approximation commonly used in engineering is to use a straight line that connects the yield point and the tensile strength point of the material. The parameters used in the subsequent calculations in addition to those defined in Section 5.1.2 are modulus of elasticity (E) and tangent (hardening) modulus (E_1). The tangent modulus represents the slope of the stress-strain curve in the plastic region.

For Ti-7, the tangent modulus is

$E_1 = (\sigma_u - \sigma_y)/(\varepsilon_u - \sigma_y/E) = (0.347 - 0.209)/(0.31 - 0.209/101) = 0.448$ GPa (at 150 °C) (see Sections 5.1.1 and 5.1.2)

Similarly, for Ti-24

$E_1 = (\sigma_u - \sigma_y)/(\varepsilon_u - \sigma_y/E) = (0.982 - 0.750)/(0.16 - 0.750/108) = 1.516$ GPa (at 150 °C) (see Sections 5.1.1 and 5.1.2)

5.2 ROCK MASS, VELOCITY, ANGLES OF IMPACT

Six different rock block data are used in this calculation (see Assumption 3.12). The mass and velocity of each rock is specified in accordance with Assumption 3.12. Three different impact points are used at angles of 40°, 60°, and 90°, measured counterclockwise about the intersection of the plane of symmetry and the top of the invert, and beginning with 0° for the top of the invert.

5.3 ROCK SHAPE AND ANGLES OF INCLINATION

The rock shape used in this calculation is that of a rectangular prism (see Assumption 3.11). The enveloping dimensions are determined as follows:

Rock block corner point coordinates (see Ref. 26 [Block Geometry Information.doc] and Assumption 3.12):
Block #2:
P2: x-coordinate = -5.34 m, y-coordinate = 4.61 m, z-coordinate = -1.10 m
P4: x-coordinate = -3.80 m, y-coordinate = 4.56 m, z-coordinate = 0.725 m
P5: x-coordinate = -4.39 m, y-coordinate = 4.60 m, z-coordinate = 1.53 m
P11: x-coordinate = -3.63 m, y-coordinate = 2.22 m, z-coordinate = 0.355 m

Therefore:

a = distance (P4 – P11) = 2.38 m
b = distance (P4 – P2) = 2.39 m
c = distance (P4 – P5) = 1.00 m

To obtain the real mass of 14.5 MT rock using its mass density, these dimensions have been slightly modified to give:

$a = 2.5$ m
$b = 2.5$ m
$c = 1.0$ m

The rest of the rock dimensions have been derived using the dimensions of the 14.5 MT rock as follows:

$d = m_2 / v_2$
$d = m_1 / v_1$

Therefore:

$v_2 / v_1 = m_2 / m_1$

where:

d = rock density
m = rock mass
v = rock volume
subscripts 1 and 2 indicate two rocks of different sizes

The dimensions of a 3.3 MT rock are calculated below:

$v_2 / v_1 = m_2 / m_1 = 3.3 / 14.5 = 0.23$

$v_2 = 0.23 * v_1 = [(0.23)^{1/3} * a_1] [(0.23)^{1/3} * b_1] [(0.23)^{1/3} * c_1]$

$v_2 = [0.61\ a_1] [0.61\ b_1] [0.61\ c_1]$

Therefore:

$a_2 = 0.61 * a_1 = 0.61 * 2.5 = 1.5$ m
$b_2 = 0.61 * b_1 = 0.61 * 2.5 = 1.5$ m
$c_2 = 0.61 * c_1 = 0.61 * 1.0 = 0.6$ m

Each rock is positioned such that its center of gravity lies directly above the point of impact. Therefore the rock inclination is determined using two dimensions of the rectangular prizm:

14.5 MT and 3.3 MT rock angle of inclination = $\arctan (c_1 / b_1) = \arctan (1.0 / 2.5) = 21.8°$

The dimensions of the 0.15 MT rock are calculated similar to above, with an exception that "c" is slightly adjusted to match the rock mass. Therefore: a = 0.5 m, b = 0.5 m, c = 0.26 m

Similarly, for the 0.11 MT rock: a = 0.5 m, b = 0.5 m, c = 0.19 m

For the 0.25 MT rock: a = 0.7 m, b = 0.7 m, c = 0.22 m

5.4 FINITE ELEMENT REPRESENTATION

The objective of this calculation is to determine the areas of residual stress that exceed 50% of the titanium material yield strength (see Section 1). These areas are calculated in the postprocessor LSTC LS-PRE/POST Version 1.0 (Beta), by visual inspection and measurement of the finite element representation.

Three-dimensional FE representations of the DS and the rocks, are developed in ANSYS V5.6.2 for six different rock sizes (see Assumption 3.12). Three different rock fall orientations have been considered: vertical, DS corner, and DS side-wall. The FE representations are developed by using the dimensions provided in Attachment I.

All of the DS components are represented by solid (brick) elements. The DS top plate and the side-walls are the most important DS components in this calculation, since all damaged areas are reported exclusively for these parts. The FE representation of the DS consists of one finely-meshed region where rock impacts take place, and other-coarsely-meshed region. The FE representation of the DS top plate has five layers of brick elements through the thickness. Furthermore, the FE mesh is refined in the impact regions in both axial and hoop directions.

The invert is modeled using rigid shell elements. The DS freely rests on the invert with a coefficient of friction specified as appropriate (see Assumptions 3.4 and 3.5). There is no lateral constraint since the gantry rail is not expected to remain intact during the 10,000-year regulatory period (Assumption 3.13). Therefore, there is no structural support for the DS side walls.

The DS corner and side-wall rock fall FE representations include the waste package positioned next to the DS side-wall inside surface. The waste package is represented by rigid shells. This boundary condition is used to obtain bounding stress results for the DS. Although the DS may not contact the waste package after a rock fall, this approach provides a rigid boundary from inside the DS side-wall inside surface.

The full-length of the drip shield is represented in the FE solutions. The rock fall occurs at the mid-length of the DS, which receives no additional support from the connector plates; hence, provides bounding results. Furthermore, the Alloy 22 base plate is excluded from the FE representation. The benefit of using this approach is to reduce the computer execution time while keeping the essential parts of the structure (Assumption 3.14). In FE representations, the thickness of the Ti-7 and Ti-24 plates and stiffeners are reduced by 2 mm, which represents the effect of corrosion during the 10,000-year regulatory period (Assumption 3.10).

The FE representation of rocks is also divided into two regions: small finely-meshed impact region and large coarsely-meshed remaining part of the rock. The continuity of deformation between two rock parts is ensured by a tied-interface contact. The fine mesh in the impact region is essential for the rock deformation. The fine mesh, coupled with elastic-ideally-plastic constitutive representation (see Section 5.4.1 for details) ensures more realistic rock deformation in the impact zone compared to the elastic rock. This approach attempts to capture the localized crushing of the rock in the contact region and the consequent load distribution over the larger DS top plate area (see Section 5.4.1).

Available contact representation features of LS-DYNA V960 FE code are used to represent contacts between: rocks and DS top plate and DS side-wall, DS side-walls and invert, and waste pacakge and DS side-walls. In absence of more appropriate data, the dynamic friction coefficients for all contacts are assumed to be 0.5 (see Assumptions 3.4 and 3.5). Moreover, the functional friction coefficient used by LS-DYNA V960 FE code is defined in terms of static and dynamic friction coefficients, and relative velocity of the surfaces in contact (Ref. 9, p. 6.9). The effect of the relative velocity of the surfaces in contact is introduced by the way of a fitting parameter - exponential decay coefficient. The variation of friction coefficient between the static and dynamic value as a function of relative velocity of the surfaces in contact is not available in literature for the materials used in this calculation. Therefore, it is not possible to objectively evaluate the exponential decay coefficient. Hence, the effect of the relative velocity of the surfaces in contact is neglected in these calculations by assuming that the functional friction coefficient and the static friction coefficient are equal to the dynamic friction coefficient. This approach provides a bounding set of results by minimizing the friction coefficient within the given FE-analysis framework (Assumption 3.6).

The specified termination times of rock-fall simulation are such to allow the rock to bounce off the DS top plate after the impact, and for an essentially steady-state to establish.

The mesh of the FE representation was appropriately generated and refined in the contact regions according to standard engineering practice. Thus, the accuracy and representativeness of the results of this calculation are deemed acceptable (see Table 6-1).

5.4.1 Constitutive Representation of Rock Behavior

In general, the constitutive representation of rock behavior (i.e., stress-strain relation) needs to address various complexities of rock deformation. In contrast to the elastic-ideally-brittle behavior of rock under tension, the stress-strain behavior of rock under compression can take numerous forms depending on the loading conditions (lateral confinement is a notable example), geometry (i.e., the slenderness ratio of the test specimen), and size. The brittle materials in general, when subjected to compression, exhibit a wide range of nonlinear stress-strain behaviors due to the nucleation, propagation, and coalescence of microcracks under different boundary conditions (see Ref. 17, Sections 4.2 through 4.5). Moreover, the compressive strength of brittle materials (including rock) is significantly higher than their tensile strength. Finally, unlike engineering metals, the rocks may exhibit nonlinear behavior even under moderate hydrostatic compression, and significant effect of size on strength (see Ref. 17; Sections 4, 6, and 7, for detailed discussion). A variety of constitutive representations is developed to address the most prominent features of the behavior of brittle materials (see Ref. 12, pages 362 and 363). These complex constitutive representations require many input parameters. Some of them are not available at present, while the others are not intrinsic properties of material but rather fitting parameters whose estimation requires unavailable data. Thus, a reasonable simplification of rock constitutive behavior is deemed necessary. Fortunately, the stress state in rocks is of no interest in this analysis - the rock deformation is important only as much as it affects the stresses and strains in the DS top plate, which is the objective of this calculation. Thus, as a first approximation, the constitutive representation of rock behavior should appropriately capture local crushing of the rock at the point of impact, resulting in distribution of impact energy over the larger contact area. It is, therefore, considered appropriate to conservatively represent the rock behavior as elastic-ideally-plastic (see Fig. 1 and Ref. 17, Section 9). This representation of nonlinear behavior seems to offer obvious advantages compared to the elastic representation, while remaining conservative under the given loading conditions. The unconfined compressive strength of rock, used as the yield strength in the constitutive representation, is one of the parameters in this study that affects the results. A conservative value of the unconfined compressive strength is therefore used to provide a bounding set of results. Having in mind that the loading conditions of the rock are predominantly compressive, 290 MPa is an appropriate upper bound of the rock strength (Assumption 3.8).

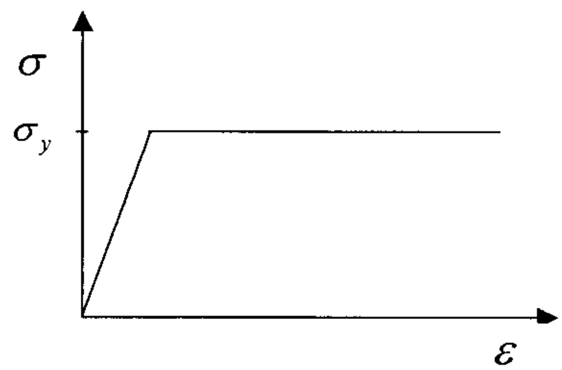


Figure 1. Elastic-Ideally-Plastic Constitutive Representation

5.5 CALCULATION OF DAMAGED AREAS

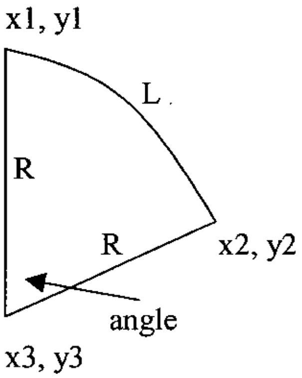
The objective of this calculation is to determine the areas of residual stress (damaged areas) that exceed 50% of the titanium material yield strength (see Section 1) (104 MPa). Illustrations of typical first principal stress distributions on the DS plates are shown in Figures II-6 and II-7. In the postprocessor, the first principal stress contours have been used to select all-rectangular areas that exceed this value. These calculations are provided below for all rocks that result in residual stresses over 104 MPa on DS plates.

5.5.1 Calculations for 10^{-6} Ground Motion

The rock fall onto drip shield causes structural damage in the drip shield components. The extent of the damage depends on the kinetic energy of the rock, which impacts the drip shield. The first part of this calculation uses 10^{-6} ground motion data to obtain a look-up table that relates the rock block kinetic energy and impact locations to the damaged area on the drip shield. The second part will determine a similar table for the 10^{-7} ground motion data.

After the rock blocks bounce off the DS surface, the residual first principal stress contours indicate that there is slight oscillation of stress around a mean value. This is caused by the fact that no damping in the DS structure was used. The purpose of this approach was to report an upper bound for the stresses by using their peak values. Therefore, the post-processing of the stress contours entails the following: subsequent to rock separation from the DS, each time step is analyzed to yield a bounding residual stress area from both surfaces of the DS plates. In other words, all areas of residual stress exceeding 104 MPa have been used in calculation of damaged areas from both inner and outer surfaces. When these areas overlap, these areas are counted as one. These areas are identified using their two corner points.

In calculating areas for the vertical rock fall case, although the effect of the DS top plate curvature is negligibly small, it is taken into account by the following approach:



angle2 = arctan [(y1 – y3) / (x1 – x3)]

angle1 = arctan [(y2 – y3) / (x2 – x3)]

angle = angle2 – angle1 = arctan [(y1 – y3) / (x1 – x3)] - arctan [(y2 – y3) / (x2 – x3)]

L = R * angle

R = 1.3 m (page I-14, DS plate radius of curvature)

x3 = 0 (plane of symmetry)

y3 = 2.886 (overall DS height) – 0.015 (plate thickness) – 0.050 (connector guide thickness) – 1.3 = 1.521 m (see pages I-2, I-19, and I-20)

L = 1.3 * [arctan [(y1 – 1.521) / (x1 – 0)] - arctan [(y2 – 1.521) / (x2 – 0)]]

14.5 MT Vertical Rock Fall Case:

For all rock fall simulations, the deformation in DS plates has no significant effect on the calculation of damaged areas. Therefore, the following calculations are based on the nodal coordinates recorded at the initial time step. This has no significant effect on the results due to small deformation of damaged areas.

Area #1:

Area corner node #45238, coordinates: (0, 2.819, -2.2959)
Area corner node #23296, coordinates: (0.55388, 2.6992, -1.5855)

$L = 1.3 * [\arctan[(y1 - 1.521) / (x1 - 0)] - \arctan[(y2 - 1.521) / (x2 - 0)]]$
$L = 1.3 * [\pi/2 - \arctan[(2.6992 - 1.521) / (0.55388 - 0)]] = 0.571$ m

Area = depth * L = (2.2959 – 1.5855) * 0.57 = 0.406 m^2

Area #2:

Area corner node #34191, coordinates: (0.55388, 2.6992, -1.7902)
Area corner node #23290, coordinates: (0.7043, 2.6173, -1.5855)

$L = 1.3 * [\arctan[(2.6992 - 1.521) / (0.55388 - 0)] - \arctan[(2.6173 - 1.521) / (0.7043 - 0)]]$

L = 0.171 m

Area = depth * L = (1.7902 – 1.5855) * 0.171 = 0.035 m^2

Area #3:

Area corner node #44697, coordinates: (0.55388, 2.6992, -2.2959)
Area corner node #28387, coordinates: (1.1398, 2.167, -2.054)

$L = 1.3 * [\arctan[(2.6992 - 1.521) / (0.55388 - 0)] - \arctan[(2.167 - 1.521) / (1.1398 - 0)]]$

L = 0.8 m

Area = depth * L = (2.2959 – 2.054) * 0.8 = 0.194 m^2

Area #4:

Area corner node #54090, coordinates: (0.27585, 2.7913, -3.255)
Area corner node #47313, coordinates: (0.89831, 2.4672, -3.123)

L = 1.3 * [arctan [(2.7913 – 1.521) / (0.27585 – 0)] - arctan [(2.4672 – 1.521) / (0.89831 – 0)]]

L = 0.709 m

Area = depth * L = (3.255 – 3.123) * 0.709 = 0.093 m^2

Area #5 (DS side-wall):

Area corner node #42951, coordinates: (1.176, 1.1294, -2.186)
Area corner node #27647, coordinates: (1.2155, 0, -2.054)

Area = (y2 - y1) * (z2 – z1) = (1.1294 – 0) * (2.186 – 2.054) = 0.149 m^2

Therefore, using areas calculated above and considering two-plane symmetry:

Total damaged area = (Area #1 + Area #2 + Area #3 + Area #4 + Area #5) * 4

Total damaged area = (0.406 + 0.035 + 0.194 + 0.093 + 0.149) * 4 = 3.508 m^2

3.3 MT Vertical Rock Fall Case:

Area #1:

Area corner node #30483, coordinates: (0, 2.819, -1.9441)
Area corner node #23311, coordinates: (0.25977, 2.7945, -1.5855)

L = 1.3 * [π/2 - arctan [(2.7945 – 1.521) / (0.25977 – 0)]] = 0.262 m

Area = depth * L = (1.9441 – 1.5855) * 0.262 = 0.094 m^2

Area #2 (DS side-wall):

Area corner node #46495, coordinates: (1.1942, 0.60813, -3.123)
Area corner node #50570, coordinates: (1.2155, 0, -3.1615)

Area = (0.60813 – 0) * (3.1615 – 3.123) = 0.023 m^2

Area #3 (DS side-wall):

Area corner node #52371, coordinates: (1.1973, 0.52125, -3.2165)
Area corner node #53509, coordinates: (1.2155, 0, -3.255)

Area = (0.52125 – 0) * (3.255 – 3.2165) = 0.020 m^2

Therefore, using areas calculated above and considering two-plane symmetry:

Total damaged area = (Area #1 + Area #2 + Area #3) * 4

Total damaged area = (0.094 + 0.023 + 0.020) * 4 = 0.548 m^2

0.15 MT Vertical Rock Fall Case:

Area corner node #26179, coordinates: (0.023231, 2.8189, -1.5758)
Area corner node #36843, coordinates: (0.061833, 2.8179, -1.5952)

Area = (1.5952 – 1.5758) (0.061833 – 0.023231) = 0.00075 m^2

Because of half-symmetry:

Total damaged area = Area * 2 = 0.00075 * 2 = 0.0015 m^2

0.11 MT Vertical Rock Fall Case:

No residual stress exists in DS. Therefore, damaged area is zero.

0.25 MT Vertical Rock Fall Case:

No residual stress exists in DS. Therefore, damaged area is zero.

14.5 MT Rock Fall onto DS Corner Case:

Area #1:

Area corner node #17531, coordinates: (0.9269, 2.4396, -1.3368)
Area corner node #31594, coordinates: (1.1398, 2.167, -1.6964)

Arc-length over the DS top plate surface is almost the same as the length of a line connecting the end points of the same arc. Therefore:

$L = [(0.9269 - 1.1398)^2 + (2.4396 - 2.167)^2]^{1/2} = 0.346$ m

Area = 0.346 * (1.6964 – 1.3368) = 0.124 m^2

Area #2 (adjacent to above area, i.e., using node #17531 for z-dimension, on the DS side-wall):

Area corner node #31594, coordinates: (1.1398, 2.167, -1.6964)
Area corner node #31630, coordinates: (1.1456, 1.999 -1.6964)

Area = (2.167 – 1.999) * (1.6964 – 1.3368) = 0.060 m^2.

Area #3:

Area corner node #28640, coordinates: (0.5894, 2.6821, -2.054)
Area corner node #41912, coordinates: (1.1408, 2.139, -2.186)
$L = [(0.5894 - 1.1408)^2 + (2.6821 - 2.139)^2]^{1/2} = 0.774$ m

Area = 0.774 * (2.186 – 2.054) = 0.102 m^2

Area #4 (DS side-wall):

Area corner node #10883, coordinates: (1.173, 1.2163, -1.051)
Area corner node #19019, coordinates: (1.1912, 0.695, -1.4963)
Area = (1.2163 – 0.695) * (1.4963 – 1.051) = 0.232 m^2

Area #5 (DS side-wall):

Area corner node #29805, coordinates: (1.173, 1.2162, -1.6747)
Area corner node #26880, coordinates: (1.1851, 0.86875, -1.9441)

Area = (1.2162 – 0.86875) * (1.9441 – 1.6747) = 0.094 m^2

Therefore, using areas calculated above:

Total damaged area = Area #1 + Area #2 + Area #3 + Area #4 + Area #5

Total damaged area = 0.124 + 0.06 + 0.102 + 0.232 + 0.094 = 0.612 m^2

3.3 MT Rock Fall onto DS Corner Case:

Area #1:

Area corner node #17551, coordinates: (0.93828, 2.4274, -1.3368)
Area corner node #31607, coordinates: (1.1437, 2.055, -1.7902)

$L = [(0.93828 - 1.1437)^2 + (2.4274 - 2.055)^2]^{1/2} = 0.4253$ m

Area = 0.4253 * (1.7902 – 1.3368) = 0.193 m^2

Area #2:

Area corner node #56444, coordinates: (0.65833, 2.6451, -4.0821)
Area corner node #56071, coordinates: (0.93828, 2.4274, -4.192)

$L = [(0.65833 - 0.93828)^2 + (2.6451 - 2.4274)^2]^{1/2} = 0.3546$ m

Area = 0.3546 * (4.192 – 4.0821) = 0.039 m^2

Area #3 (DS side-wall):

Area corner node #26855, coordinates: (1.1699, 1.3031, -2.054)
Area corner node #42790, coordinates: (1.1821, 0.95563, -2.2959)

Area = (1.3031 – 0.95563) * (2.2959 – 2.054) = 0.084 m^2

Area #4 (DS side-wall):

Area corner node #10866, coordinates: (1.1699, 1.3031, -1.033)
Area corner node #15408, coordinates: (1.2033, 0.3475, -1.117)
Area = (1.3031 – 0.3475) * (1.117 – 1.033) = 0.080 m^2

Area #5 (DS side-wall):

Area corner node #4028, coordinates: (1.1942, 0.60813, -0.0095)
Area corner node #5145, coordinates: (1.2124, 0.08688, -0.048)

Area = (0.60813 – 0.08688) * (0.048 – 0.0095) = 0.020 m^2

Therefore, using areas calculated above:

Total damaged area = Area #1 + Area #2 + Area #3 + Area #4 + Area #5

Total damaged area = 0.193 + 0.039 + 0.084 + 0.080 + 0.020 = 0.416 m^2

0.15 MT Rock Fall onto DS Corner Case:

Area corner node #22535, coordinates: (1.0522, 2.3054, -1.5621)
Area corner node #31599, coordinates: (1.1398, 2.167, -1.6179)

$L = [(1.0522 - 1.1398)^2 + (2.3054 - 2.167)^2]^{1/2} = 0.1638$ m

Area = 0.1638 * (1.6179 – 1.5621) = 0.0091 m^2

Total damaged area = 0.0091 m^2

0.11 MT Rock Fall onto DS Corner Case:

No residual stress exists in DS. Therefore, damaged area is zero.

0.25 MT Rock Fall onto DS Corner Case:

No residual stress exists in DS. Therefore, damaged area is zero.

14.5 MT Rock Fall onto DS Side-wall Case:

Area corner node #23624, coordinates: (1.175, 1.1583, -1.4746)
Area corner node #36406, coordinates: (1.1861, 0.83979, -1.7223)

Area = (1.1583 – 0.83979) * (1.7223 – 1.4746) = 0.079 m^2
Total damaged area = 0.079 m^2

3.3 MT Rock Fall onto DS Side-wall Case:

No residual stress exists in DS. Therefore, damaged area is zero.

0.15 MT Rock Fall onto DS Side-wall Case:

No residual stress exists in DS. Therefore, damaged area is zero.

0.11 MT Rock Fall onto DS Side-wall Case:

No residual stress exists in DS. Therefore, damaged area is zero.

0.25 MT Rock Fall onto DS Side-wall Case:

No residual stress exists in DS. Therefore, damaged area is zero.

5.5.2 Calculations for 10^{-7} Ground Motion

The analyses of drip shield response to rock blocks from the 10^{-6} ground motion are used to obtain a look-up table that relates the rock block kinetic energy and impact locations to the damaged area on the drip shield. Additional LS-DYNA simulations are also performed for the maximum rock block ejected by the 10^{-7} ground motions. This rock size and velocity was obtained from Reference 26 (see Assumption 3.12). The damaged areas for the vertical, corner, and side-wall cases are calculated below. The method of determining damaged areas are essentially the same as what was described in Section 5.5.1 with one exception that the magnitude of stress oscillations are greater due to larger deformations on the DS plates. Therefore, the maximum areas of residual stress are used by inspection of each time step subsequent to the separation of rock from the DS.

11.5 MT Vertical Rock Fall Case:

Area:

Area corner node #27357, coordinates: (0, 2.819, -1.5855)

Area corner node #44467, coordinates: (1.1222, 2.2276, -2.4058)

L = 1.3 * [arctan [(y1 – 1.521) / (x1 – 0)] - arctan [(y2 – 1.521) / (x2 – 0)]]
L = 1.3 * [π/2 - arctan [(2.2276 – 1.521) / (1.1222 – 0)]] = 1.312 m

Area = depth * L = (2.4058 – 1.5855) * 1.312 = 1.076 m^2

Total damaged area = (Area) * 4

Total damaged area = (1.076) * 4 = 4.304 m^2

11.5 MT Rock Fall onto DS Corner Case:

Area #1:

Area corner node #23878, coordinates: (0.6356, 2.6579, -1.5855)
Area corner node #42033, coordinates: (1.1389, 2.1812, -2.186)

Arc-length over the DS top plate surface is almost the same as the length of a line connecting the end points of the same arc. Therefore:

$L = [(1.1389 - 0.6356)^2 + (2.1812 - 2.6579)^2]^{1/2} = 0.6932$ m

Area = 0.6932 * (2.186 – 1.5855) = 0.416 m^2

Area #2 (adjacent to above area, i.e., using node #23878 for z-dimension, on the DS side-wall):

Area corner node #42033, coordinates: (1.1389, 2.1812, -2.186)
Area corner node #41827, coordinates: (1.149, 1.903, -2.186)

Area = (2.1812 – 1.903) * (2.186 – 1.5855) = 0.167 m^2

Area #3 (DS side-wall):

Area corner node #41623, coordinates: (1.1669, 1.39, -2.186)
Area corner node #8559, coordinates: (1.2155, 0, -0.985)

Area = (1.39 – 0) * (2.186 – 0.985) = 1.669 m^2

Therefore, using areas calculated above:

Total damaged area = (Area #1 + Area #2) * 2 + Area #3

Total damaged area = (0.416 + 0.167) * 2 + + 1.669 = 2.835 m^2

11.5 MT Rock Fall onto DS Side-wall Case:

The post-processing of this case is performed slightly different than the rest of those given above. The rock size is large; however, its velocity is small (0.295 m/s, see Assumption 3.12). Subsequent to the lateral impact of the rock block, the rock moves down to the ground with no separation from the DS side-wall. The rock block applies a shear load on the DS side-wall due to friction. Therefore, the largest residual stress state at 0.186 s is used to calculate the damaged area:

Area corner node #13387, coordinates: (1.1539, 1.39, -1.069)
Area corner node #47531, coordinates: (1.1923, 0.2896, -2.0925)

Total damaged area = (1.39 – 0.2896) * (2.0925 – 1.069) = 1.126 m^2

5.6 CALCULATION OF DRIP SHIELD SURFACE AREA

Top plate half arc-length = [(1.98657 / 2) / 1.3] = 49.82° (see page I-14)

Top plate area = (2 * 49.82) * (π / 180) * (1.3) * (5.805) = 13.1237 m^2 (see page I-2)

Two side wall areas = 2 * (2.16563) * (5.805) = 25.1430 m^2 (see page I-13)

Therefore:

Total area = 13.1237 + 25.1430 = 38.2667 m^2

6. RESULTS

LS-DYNA stress results include high-frequency response. For verification of FE-representation cases, Figures II-2 and II-4, the results are filtered using a Butterworth low-pass filter with cut-off frequency of 60 Hz. The purpose of the filtering is to remove the high-frequency response. Since the stress results after the filtering produced steady values anticipated by visual inspection of unfiltered (raw) stress histories, this type of filtering was deemed acceptable.

Attachment III includes the input files and results files that show execution of the programs occurred correctly. The postprocessor LSTC LS-PRE/POST Version 1.0 (Beta) was used in such a way that the residual stress area coordinates were measured interactively. Then, these coordinates were used to calculate the residual stress areas as provided in Section 5.5.

An initial study of the FE mesh is performed to verify the objectivity of the mesh, i.e., that the calculation results are not mesh-sensitive. Table 6-1 shows the maximum (peak) stress intensity and the maximum first principal stress for two different FE meshes. The stress histories presented in Table 6-1 refer to the elements in which the maximum (peak) value of corresponding parameters is attained after the rock impact in the DS top plate in the course of the drop simulation.

In Table 6-1, the values of stress are presented for two different meshes. The first mesh is obtained by following the corresponding guidance in Reference 18 (Section 6.2.3). The second mesh is a refined version of the first mesh. The DS top plate element volume at the point of impact in the first mesh is 67% larger than the corresponding element in the second mesh ($5.148 * 10^{-8} / 3.089 * 10^{-8} = 1.67$). Specifically, the numbers of divisions in the axial, tangential, and thickness directions are increased from 14 to 16, from 4 to 5, and from 5 to 6, respectively; see corresponding ANSYS input files in Attachment III (mesh4 and mesh3). Note that the coordinate points and the resulting volumes of individual elements at the point of impact can be directly verified by using LS-PRE/POST. The calculation results presented in Table 6-1 indicate that the reduction of the element-size area by 67% in the contact region results in negligible effect on the stress intensity, especially considering the fact that no system damping was used, which would reduce the stress magnitudes. The original FE mesh is, therefore, deemed acceptable, and all remaining calculations are performed with the coarser mesh.

Table 6-1 Stress Intensity and First Principal Stress for Two Different FE-representation Meshes (14.5 MT Vertical Rock Fall)

	Stress Intensity (MPa)	**First Principal Stress (MPa)**
First Mesh V = 1.67 V0	346 (Fig II-2)	340 (Fig II-1)
Second Mesh V = V0	352 (Fig II-4)	363 (Fig II-3)
Difference (%)	1.7	6.3

Table 6-2 shows the results of LS-DYNA finite element evaluations for the 10^{-6} ground motion rock fall on drip shield. The damaged areas have been calculated using the regions of residual first principal stress, which exceed 50% of the Ti-7 yield strength at 150 °C (see Section 5.5).

Table 6-2 LS-DYNA Finite Element Analysis Results for Seismic Rock Fall on Drip Shield (10^{-6} Ground Motion)

Rock Mass and Kinetic Energy	Damaged Area (m^2) and Ratio of Damaged Area to Total DS Surface Area		
	Vertical Rock Fall (90° from horizontal)	Rock Fall onto DS Corner (60° from horizontal)	Rock Fall onto DS Side-wall (40° from horizontal)
14.5 MT Rock (163083 J)	3.508 (9.17%)	0.612 (1.60%)	0.079 (0.21%)
3.3 MT Rock (24712 J)	0.548 (1.43%)	0.416 (1.09%)	0.0 (0.00%)
0.15 MT Rock (902 J)	0.0015 (0.00%)	0.0091 (0.02%)	0.0 (0.00%)
0.11 MT Rock (42 J)	0.0 (0.00%)	0.0 (0.00%)	0.0 (0.00%)
0.25 MT Rock (~0 J)	0.0 (0.00%)	0.0 (0.00%)	0.0 (0.00%)

MT: metric tons (1 MT = 1000 kg)

Table 6-3 shows the results of LS-DYNA finite element evaluations for the 10^{-7} ground motion rock fall on drip shield. This additional look-up table can be used in conjunction with Table 6-2 to determine the structural response of DS to rock falls in terms of the rock blocks (mass and velocity, i.e., kinetic energy) and the damaged areas.

All of the results indicate that larger kinetic energy of the rock causes an increase in the damaged area, as expected. There is one notably large damaged area increase in the case of the 10^{-7} ground motion rock fall onto the DS corner (see Table 6-3) relative to other cases. The reason for this is a localized deformation of the DS side-wall subjected to the substantially large vertical load from the rock block.

This phenomenon is, however, observed mildly in case of the 10^{-6} ground motion simulations (see Table 6-2).

Table 6-3 LS-DYNA Finite Element Analysis Results for Seismic Rock Fall on Drip Shield (10^{-7} Ground Motion)

Rock Mass and Kinetic Energy	Damaged Area (m^2) and Ratio of Damaged Area to Total DS Surface Area		
	Vertical Rock Fall (90° from horizontal)	Rock Fall onto DS Corner (60° from horizontal)	Rock Fall onto DS Side-wall (40° from horizontal)
11.5 MT Rock (348174 J)	4.304 (11.25%)	2.835 (7.41%)	1.126 (2.94%)

MT: metric tons (1 MT = 1000 kg)

The maximum vertical displacement in the DS components takes place in the longitudinal stiffener during the 11.5 MT vertical rock fall on DS. The reason for this result is the fact that the kinetic energy of this rock block is the largest. Figure II-5 shows that the maximum displacement is 25.4 cm.

The output values are reasonable for the given inputs in this calculation. Where uncertainties are not specified, they are taken into account by consistently using the most conservative approach; the calculations, therefore, yield a bounding set of results. The results are suitable for assessment of the damaged areas over the DS.

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8. ATTACHMENTS

Attachment I (24 pages): Design sketch (*Interlocking Drip Shield* [SK-0230 REV 00, 24 sheets])

Attachment II (4 pages): Figures obtained from LS-DYNA V960

Attachment III (Compact Disc 1 of 1): ANSYS V5.6.2 and LS-DYNA V960 electronic files

Table 8-1 provides a list of attachments submitted in the form of electronic files (compact disc) in Attachment III.

Table 8-1. List of Attachments Submitted in the Form of Electronic Files in Attachment III

Directory (Name of Each Case)	Name	Date	Time	Size
c1mesh4 (14.5 MT vertical rock fall case)	mesh4.k	01/21/03	3:51 p.m.	5 KB
	messag	01/21/03	3:51 p.m.	24 KB
	elem.inc	01/21/03	3:53 p.m.	6182 KB
	node.inc	01/21/03	3:51 p.m.	5453 KB
	bc1.inc	01/21/03	3:53 p.m.	17 KB
	bc2.inc	01/21/03	3:53 p.m.	2 KB
	rock1e.inc	01/21/03	3:50 p.m.	1115 KB
	rock1n.inc	01/21/03	3:50 p.m.	946 KB
	rock1bc.inc	01/21/03	3:50 p.m.	5 KB
	rock.inp	01/22/03	12:53 p.m.	4 KB
	rock.old.out	01/22/03	12:53 p.m.	32 KB
	mesh4.inp	01/22/03	12:54 p.m.	36 KB
	mesh4.old.out	01/22/03	12:53 p.m.	159 KB
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	segmen12.inc	01/21/03	3:50 p.m.	65 KB
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	segmen13.inc	01/21/03	4:50 p.m.	24 KB
	segmen14.inc	01/21/03	4:50 p.m.	88 KB
c16 (11.5 MT vertical rock fall case)	th13c16r.k	02/08/03	1:31 p.m.	5 KB
	messag	02/08/03	1:33 p.m.	18 KB
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	node.inc	02/08/03	1:33 p.m.	5464 KB
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	bc2.inc	02/08/03	1:34 p.m.	4 KB
	rock1e.inc	02/08/03	1:32 p.m.	1115 KB
	rock1n.inc	02/08/03	1:31 p.m.	946 KB
	rock1bc.inc	02/08/03	1:32 p.m.	5 KB
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	rock.old.out	02/08/03	1:25 p.m.	32 KB
	th13c16.inp	02/08/03	1:25 p.m.	36 KB
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	segmen12.inc	02/08/03	1:31 p.m.	65 KB

c17 (11.5 MT rock fall onto DS corner case)	th13c17.k	02/08/03	1:26 p.m.	5 KB
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	rock1n.inc	02/08/03	1:26 p.m.	311 KB
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c18 (11.5 MT rock fall onto DS side-wall case)	th13c18r.k	02/09/03	1:25 p.m.	6 KB
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NOTE: The file sizes may vary with operating system.

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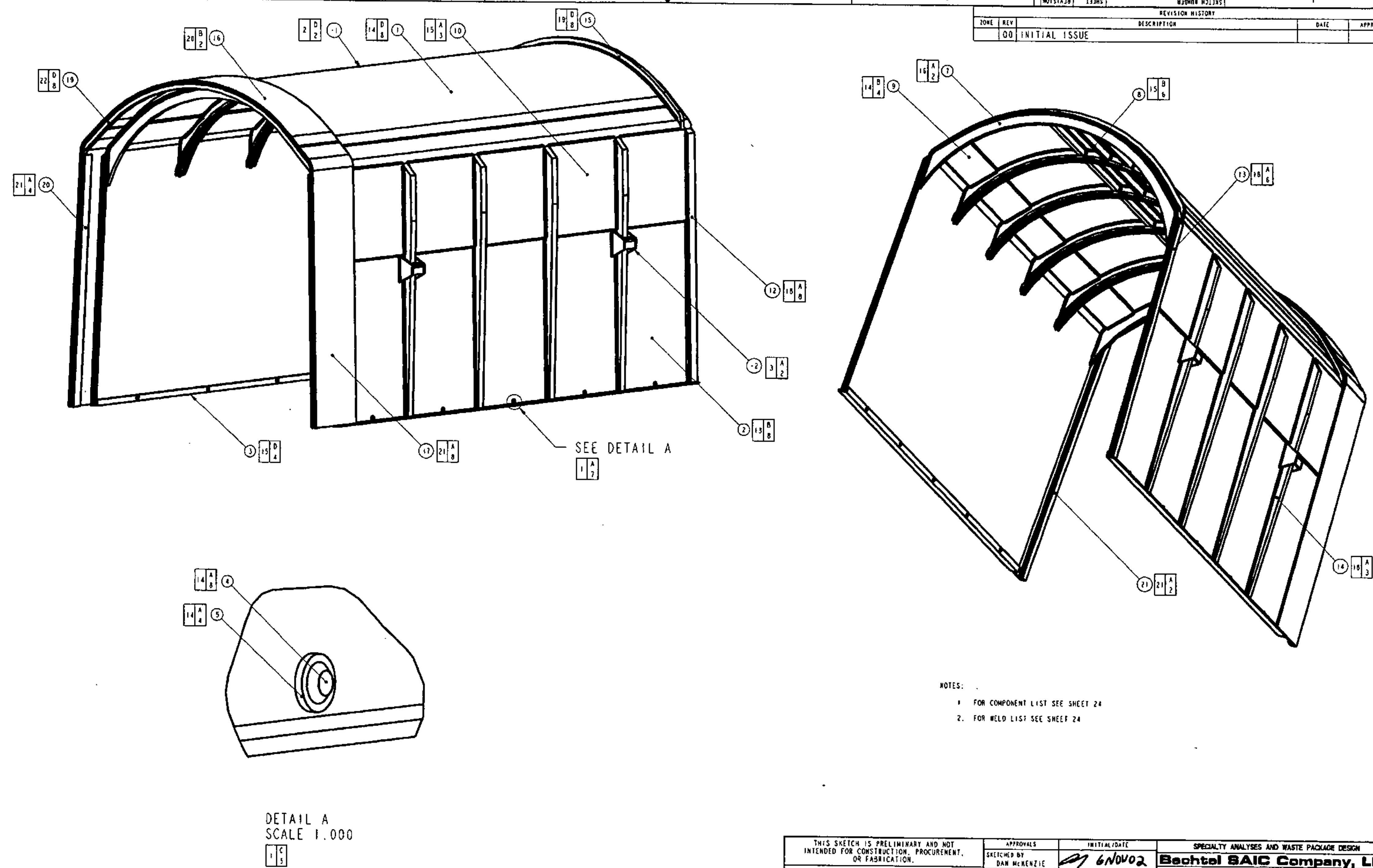

NOTES:
1. FOR COMPONENT LIST SEE SHEET 24
2. FOR WELD LIST SEE SHEET 24

THIS SKETCH IS PRELIMINARY AND NOT INTENDED FOR CONSTRUCTION, PROCUREMENT, OR FABRICATION.	APPROVALS	INITIAL/DATE	SPECIALTY ANALYSES AND WASTE PACKAGE DESIGN Bechtel SAIC Company, LLC
ALL DIMENSIONS SHOWN ARE BASIC DIMENSIONS THICKNESS CALCULATED FROM THE DIMENSIONS SHOWN IN THIS SKETCH ARE MINIMUMS. FOR CALCULATIONS AND ANALYSES IT IS UP TO THE ORIGINATOR TO DETERMINE APPROPRIATE TOLERANCES	SKETCHED BY DAN McKENZIE	6NOV02	TITLE INTERLOCKING DRIP SHIELD
	CHECKED BY ZEKAI CEYLAN	Z.C. 11/6/02	
DIMENSIONS ARE IN MILLIMETERS AND DEGREES UNLESS OTHERWISE NOTED. INCH DIMENSIONS IN BRACKETS.	APPROVED BY ADAM SCHEIDER	AKS/NOV6,2002	
	MANUFACTURING MGR JERRY COGAR	11/6/02	SKETCH NUMBER SK-0230 / REVISION 00
DO NOT SCALE FROM SKETCH	SA & WPD MGR MICHAEL ANDERSON	11/6/02	SCALE NONE / SHEET 1 OF 24

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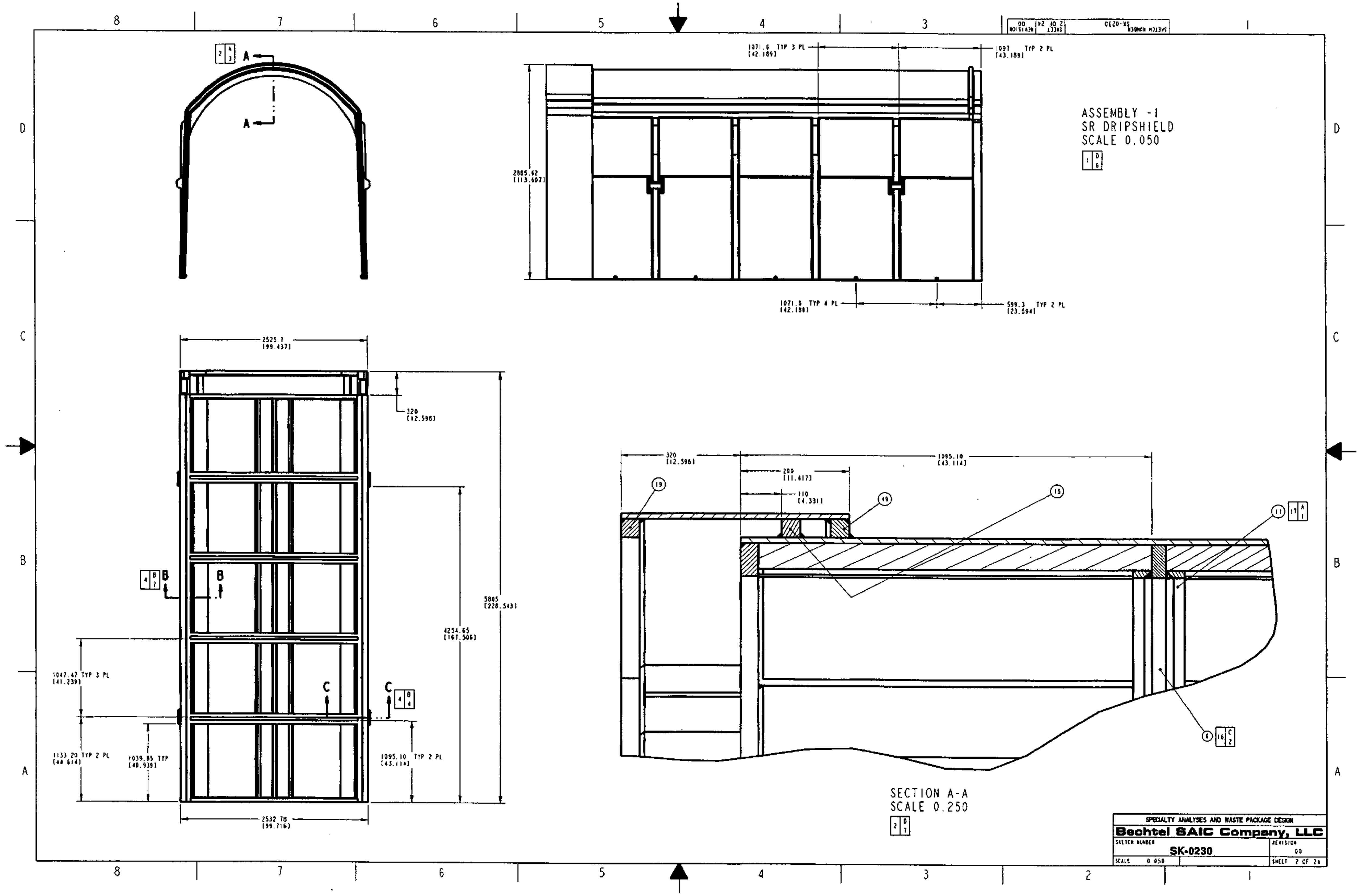

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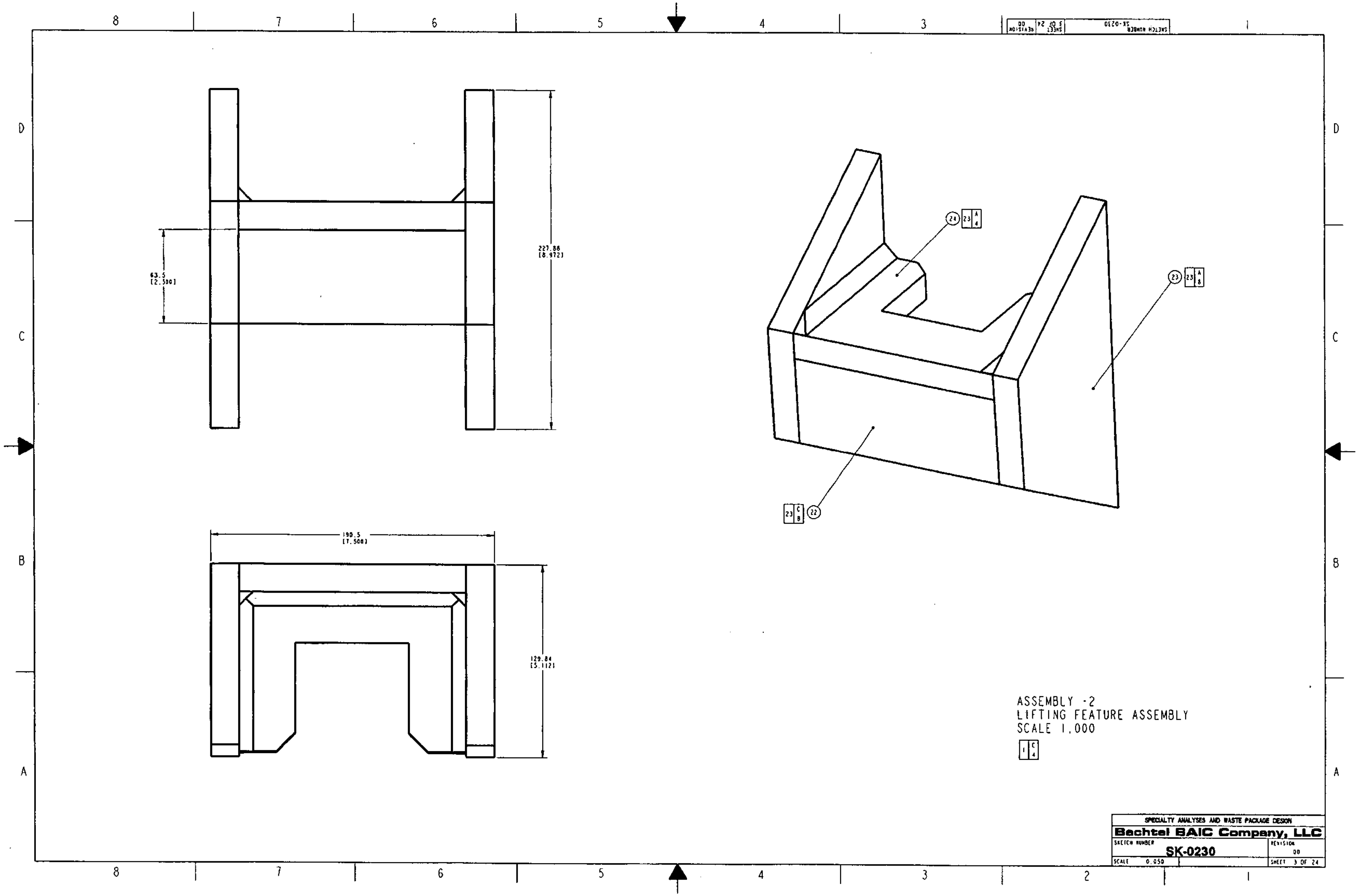

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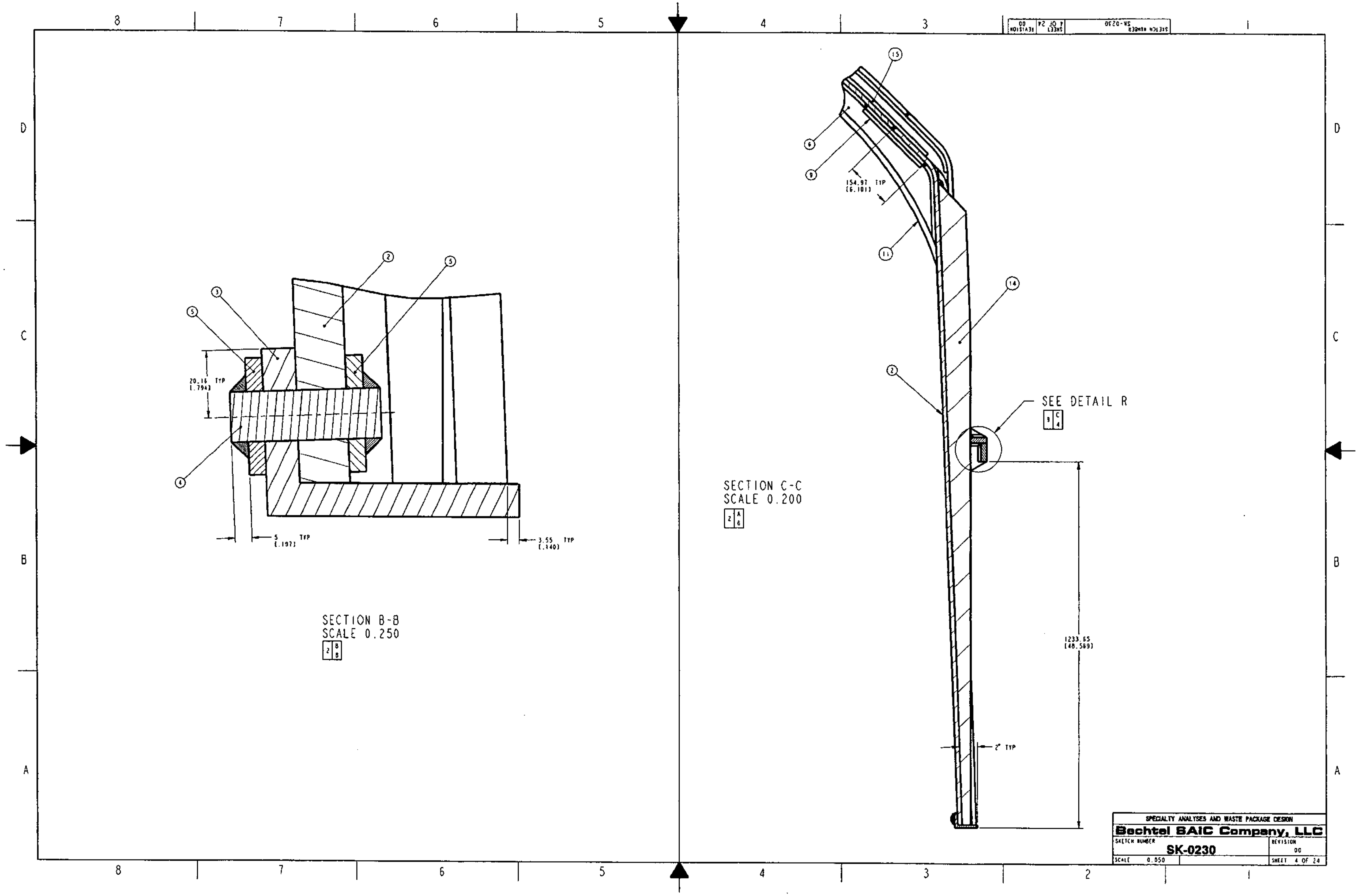

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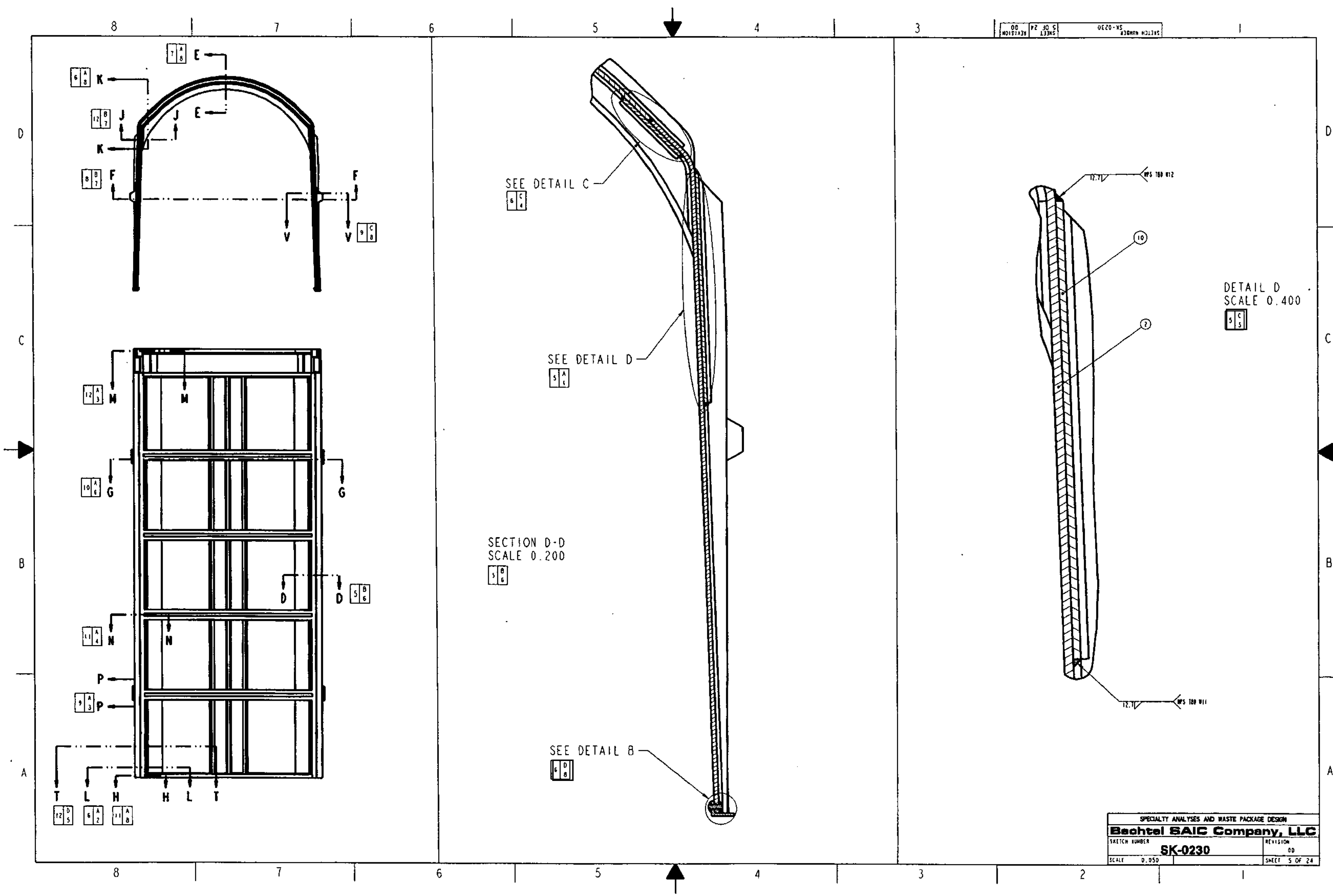

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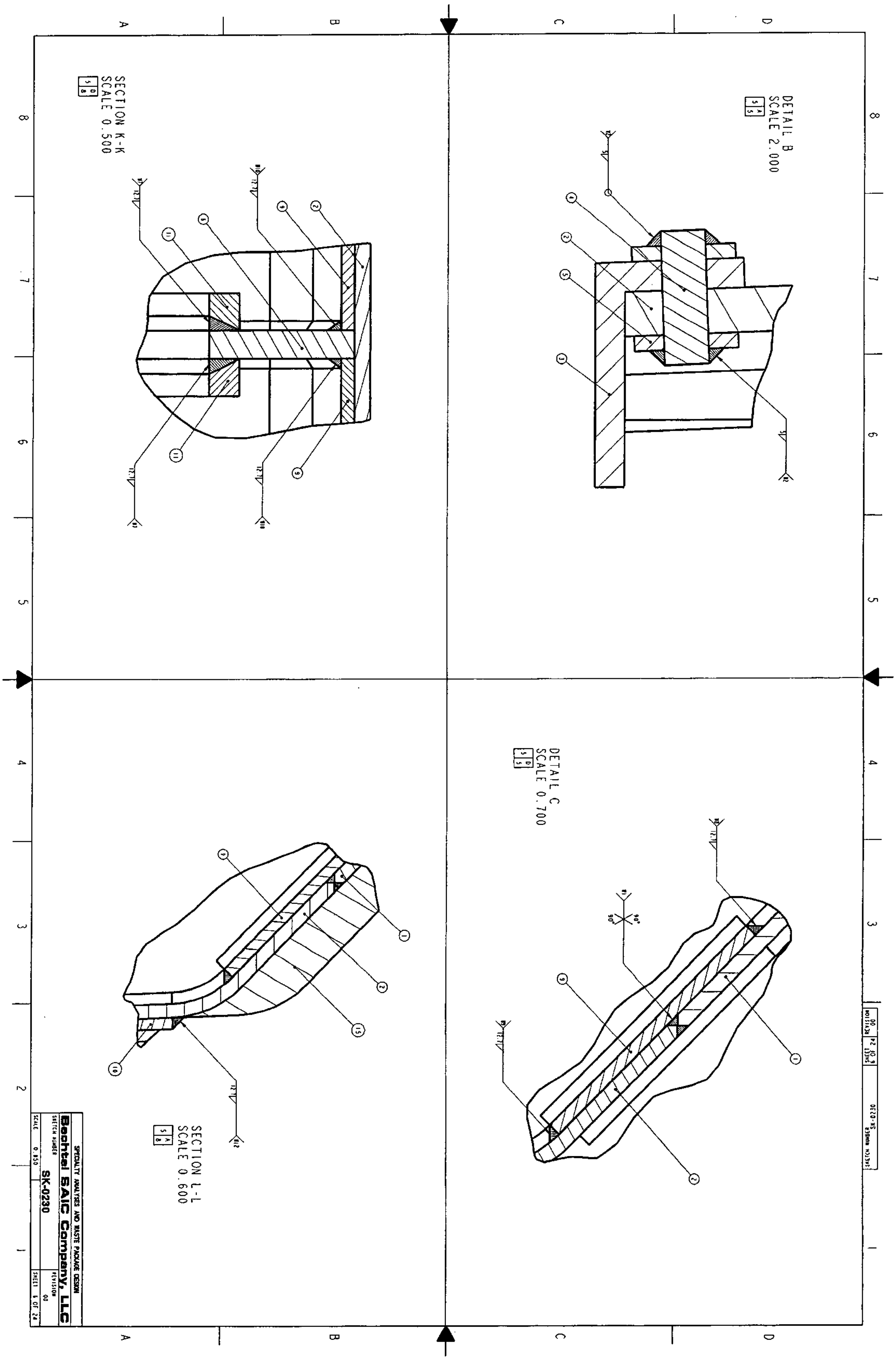

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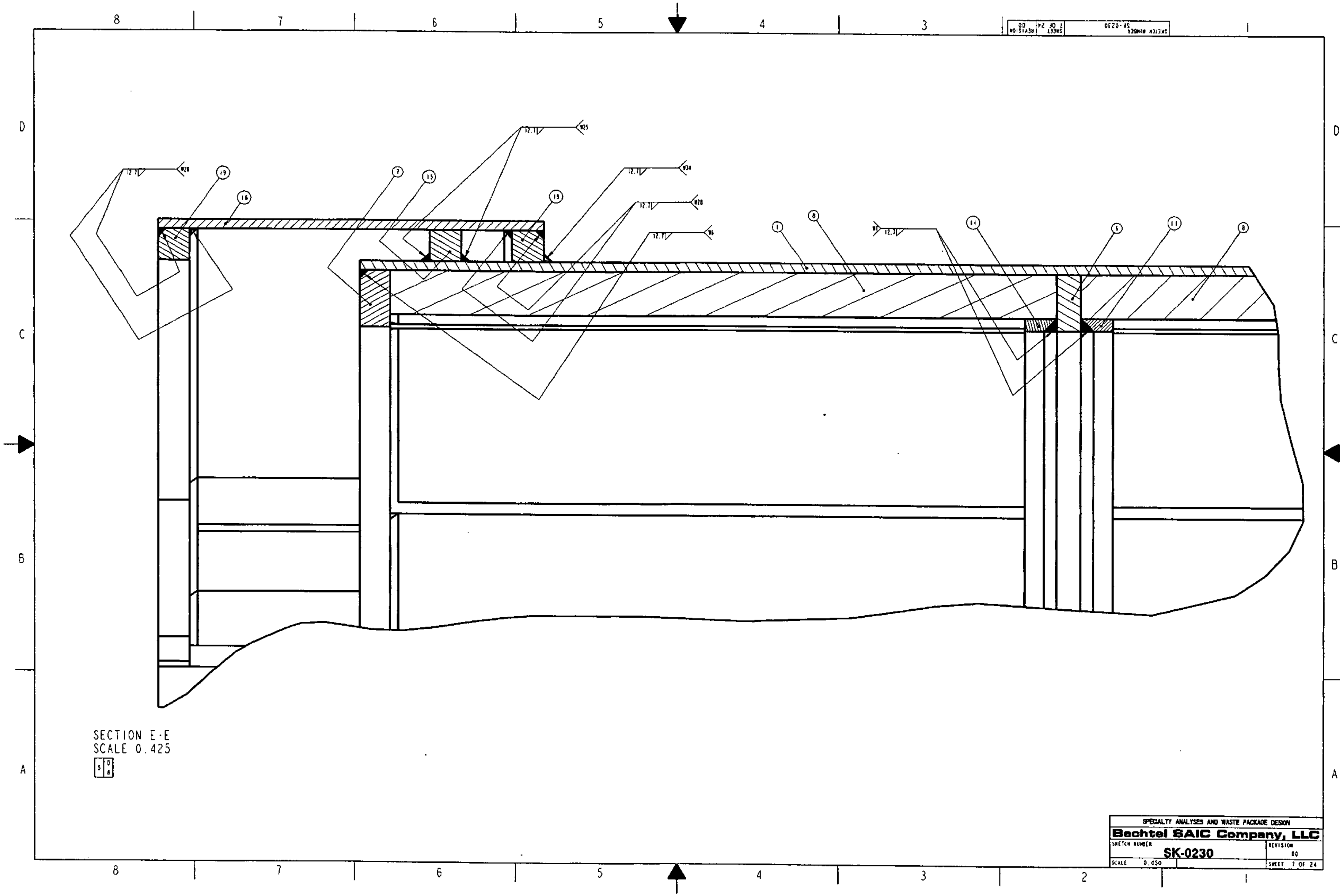

Attachment I: SK-0230 REV 00 – Interlocking Drip Shield

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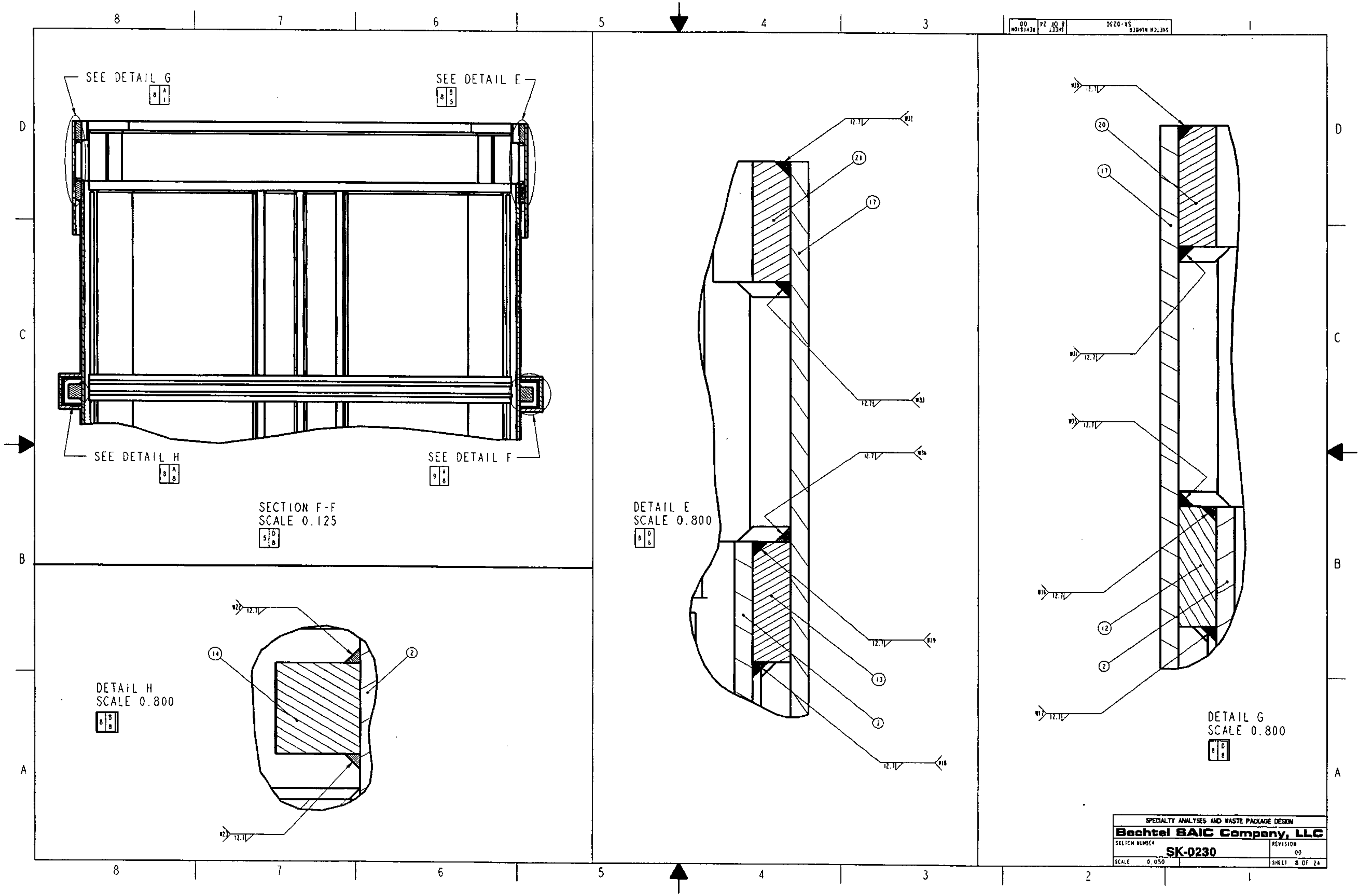

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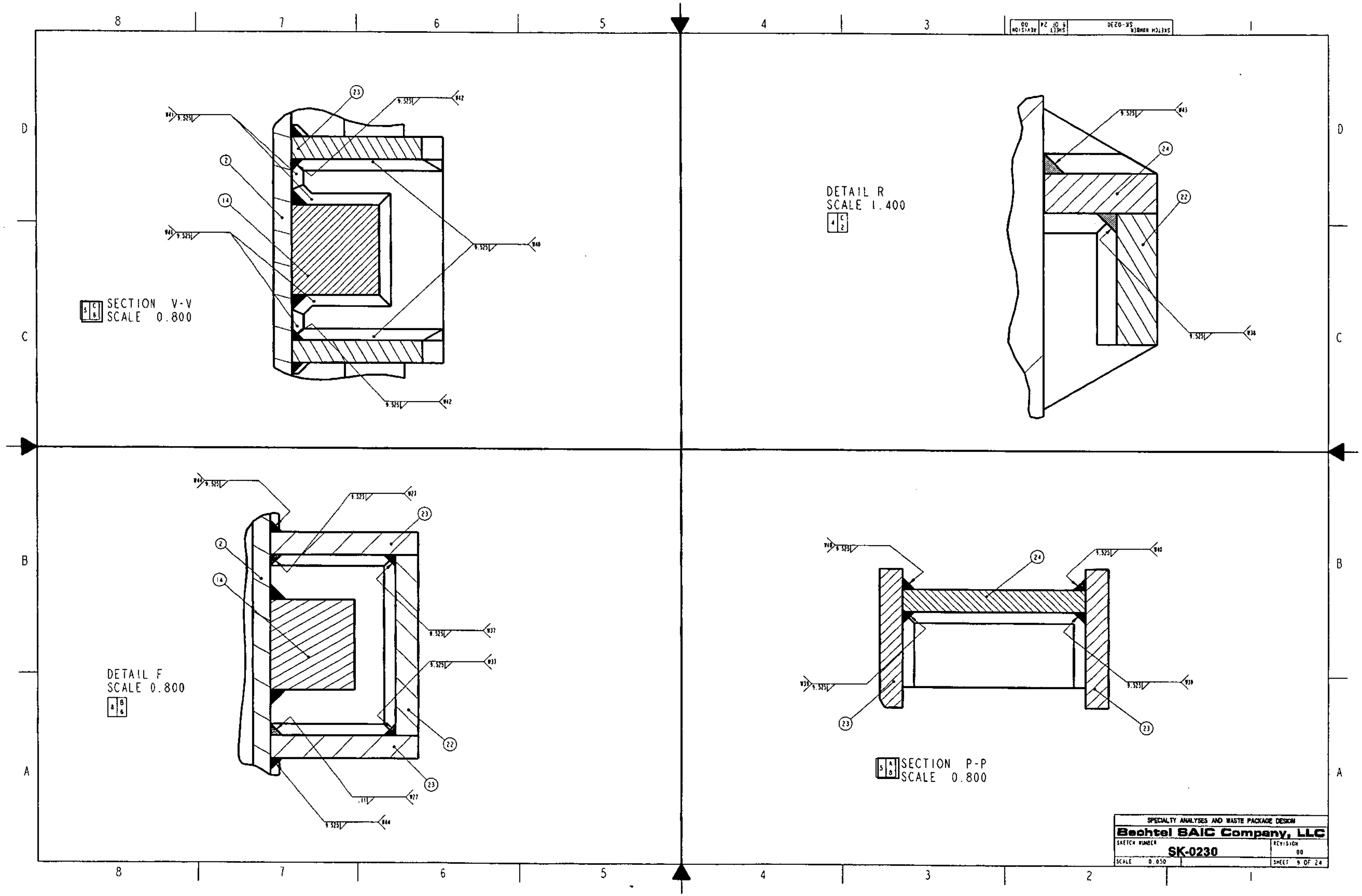

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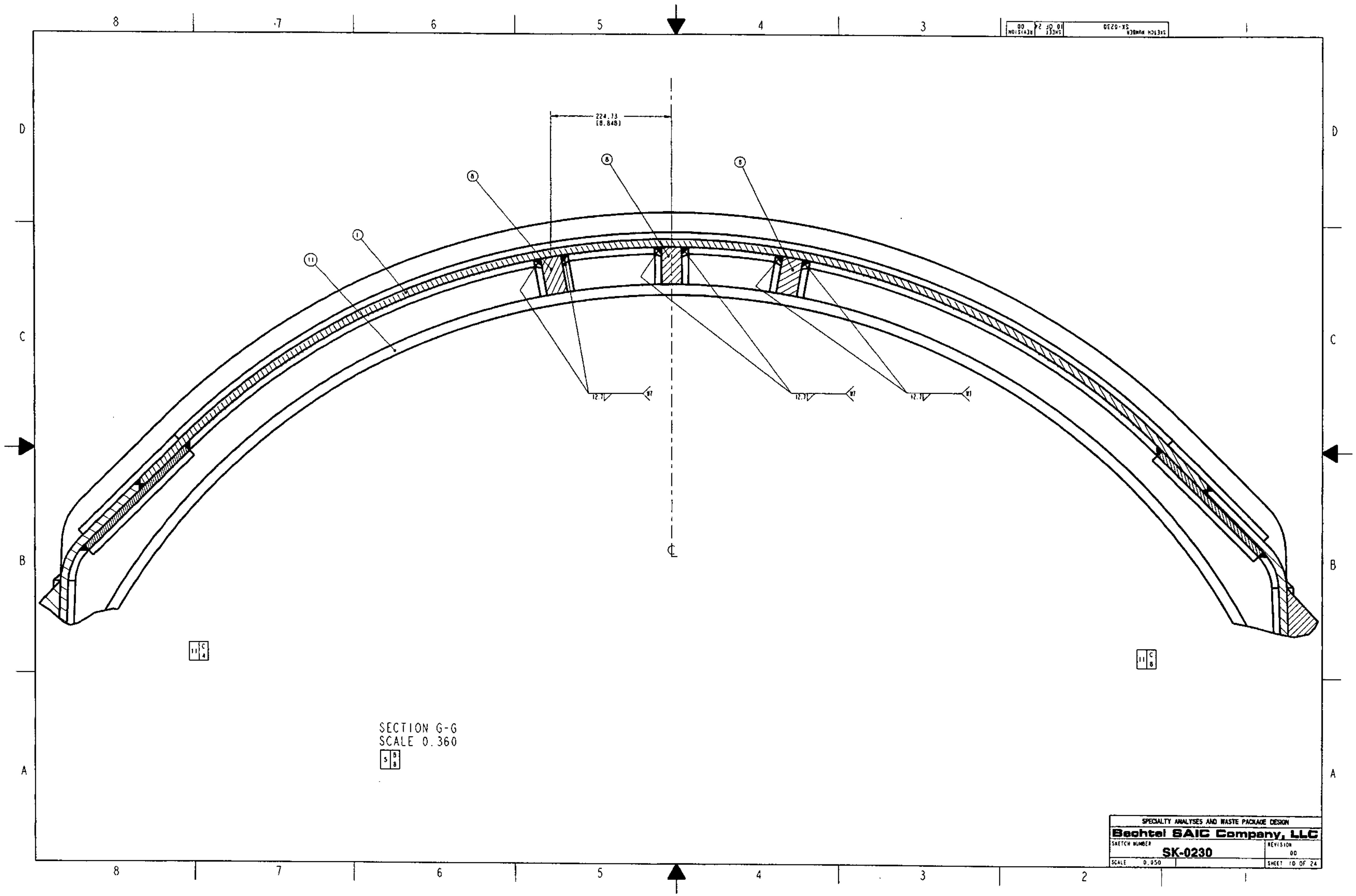

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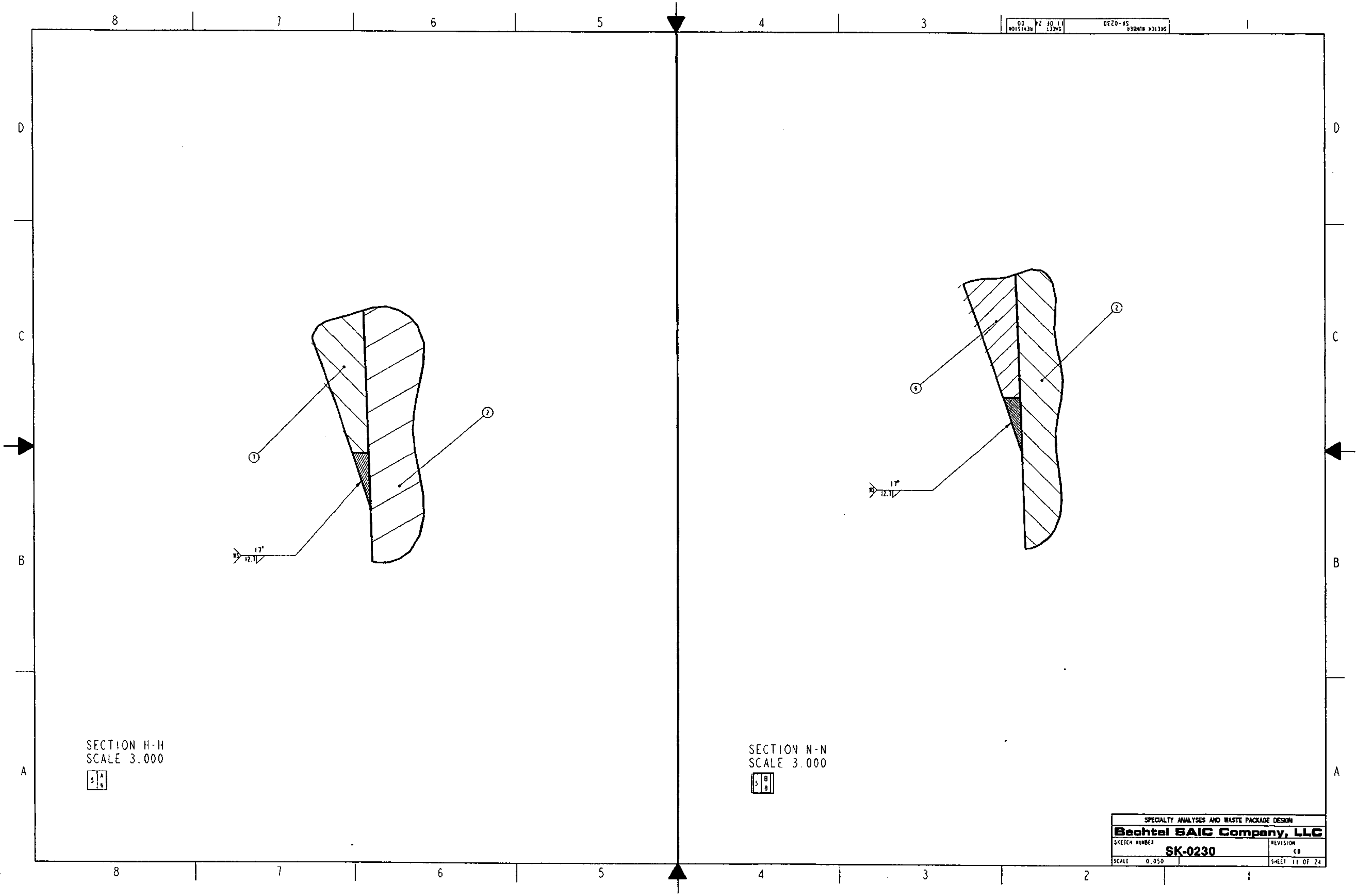

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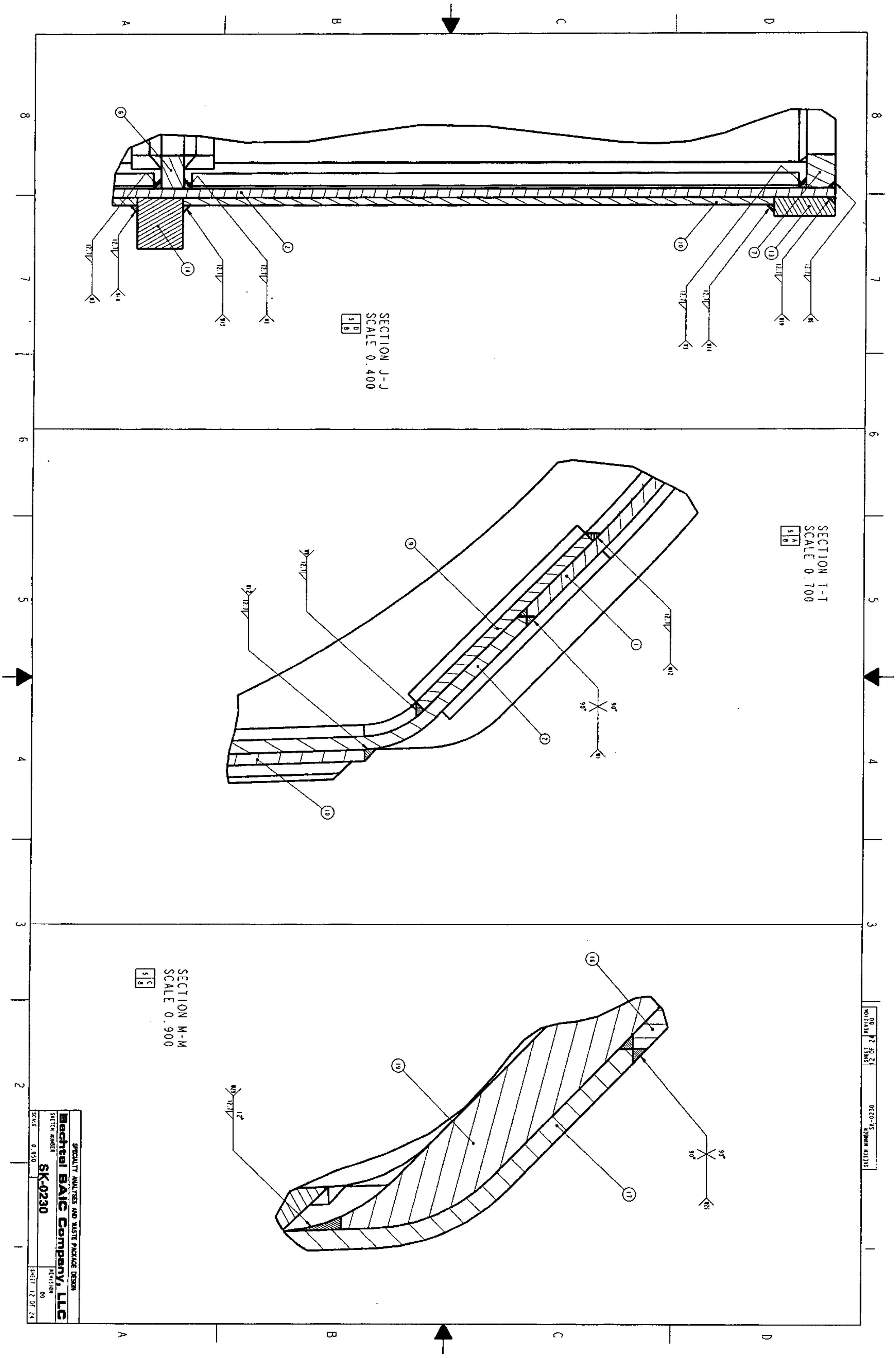

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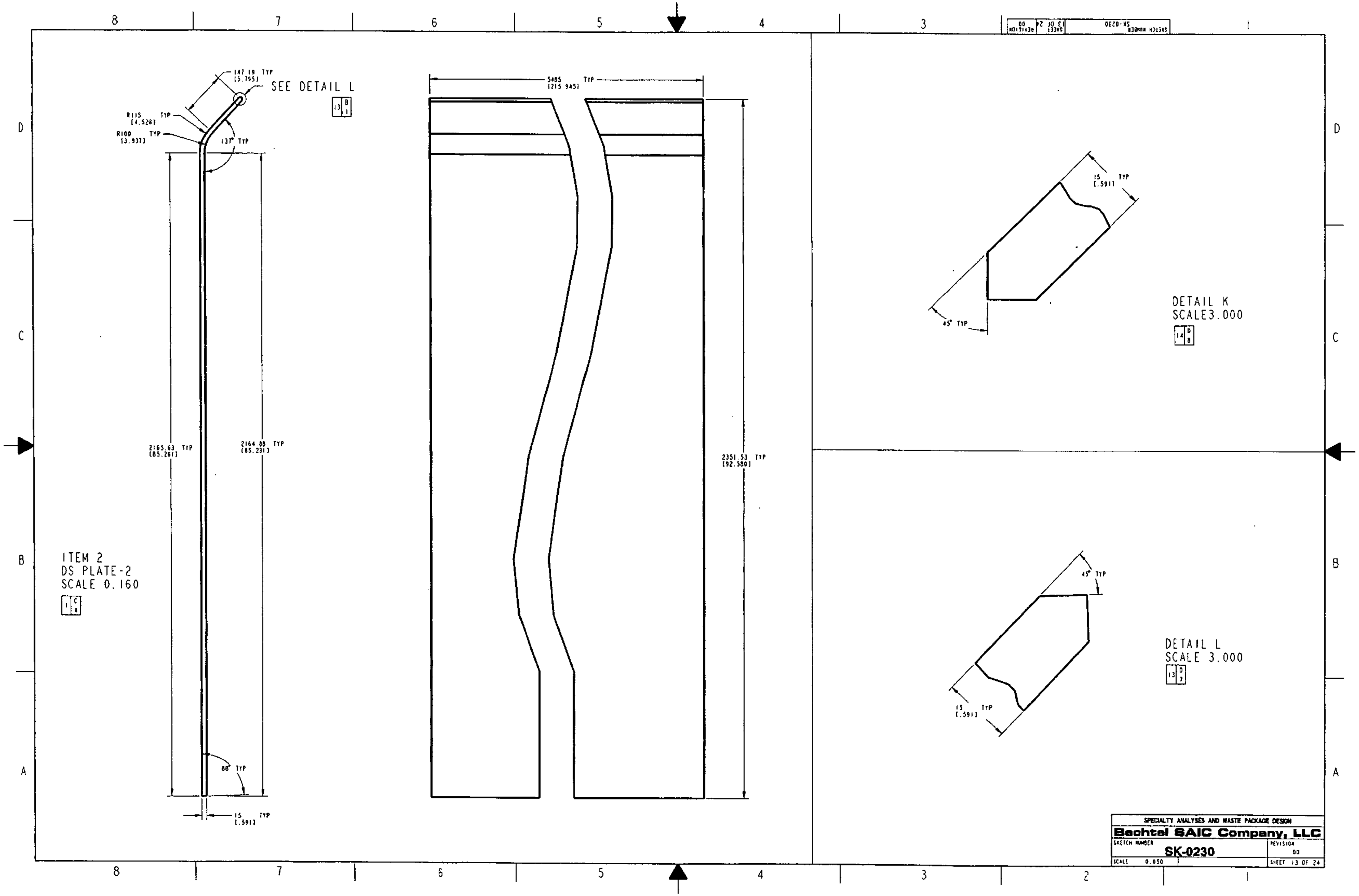

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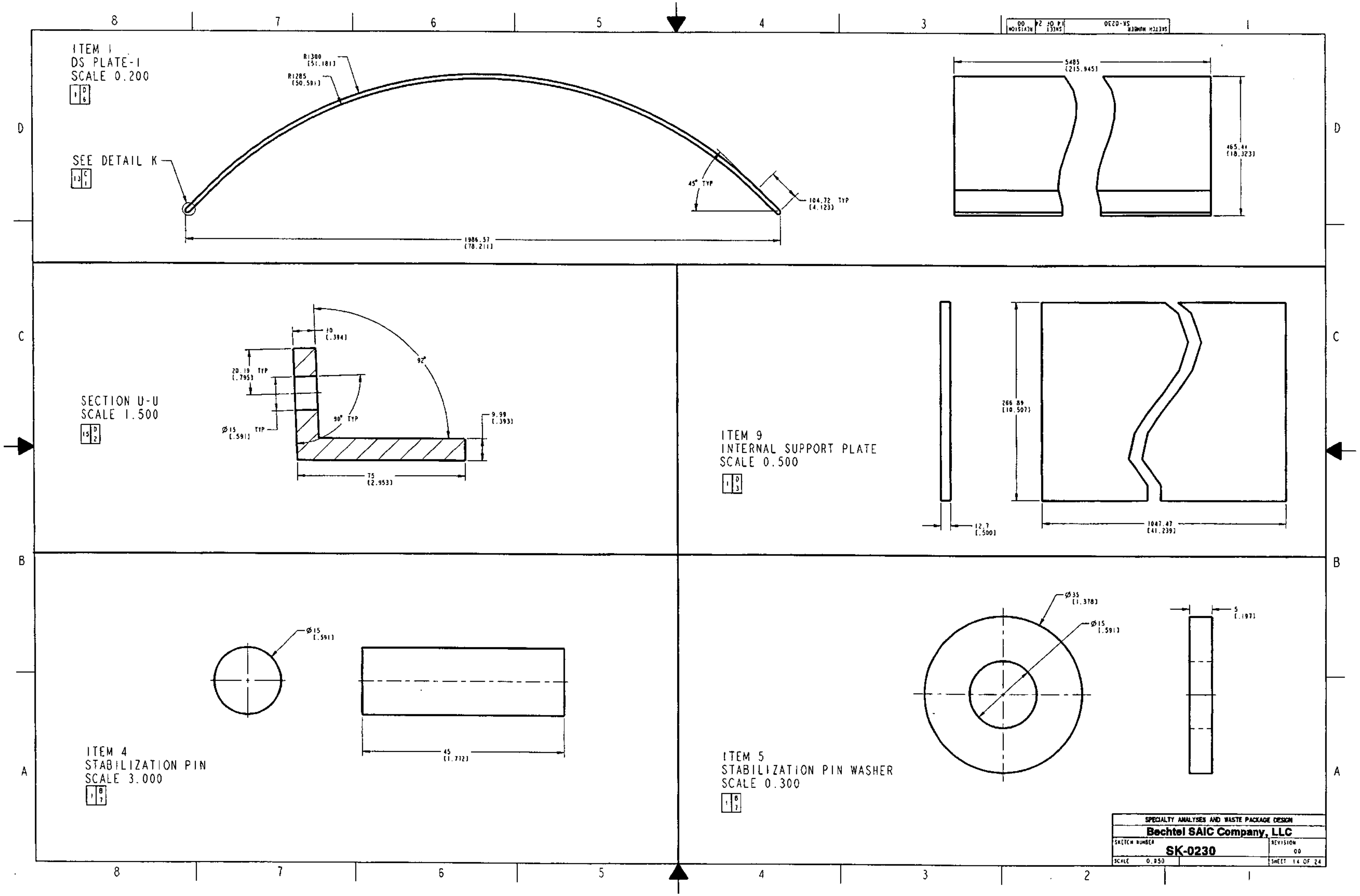

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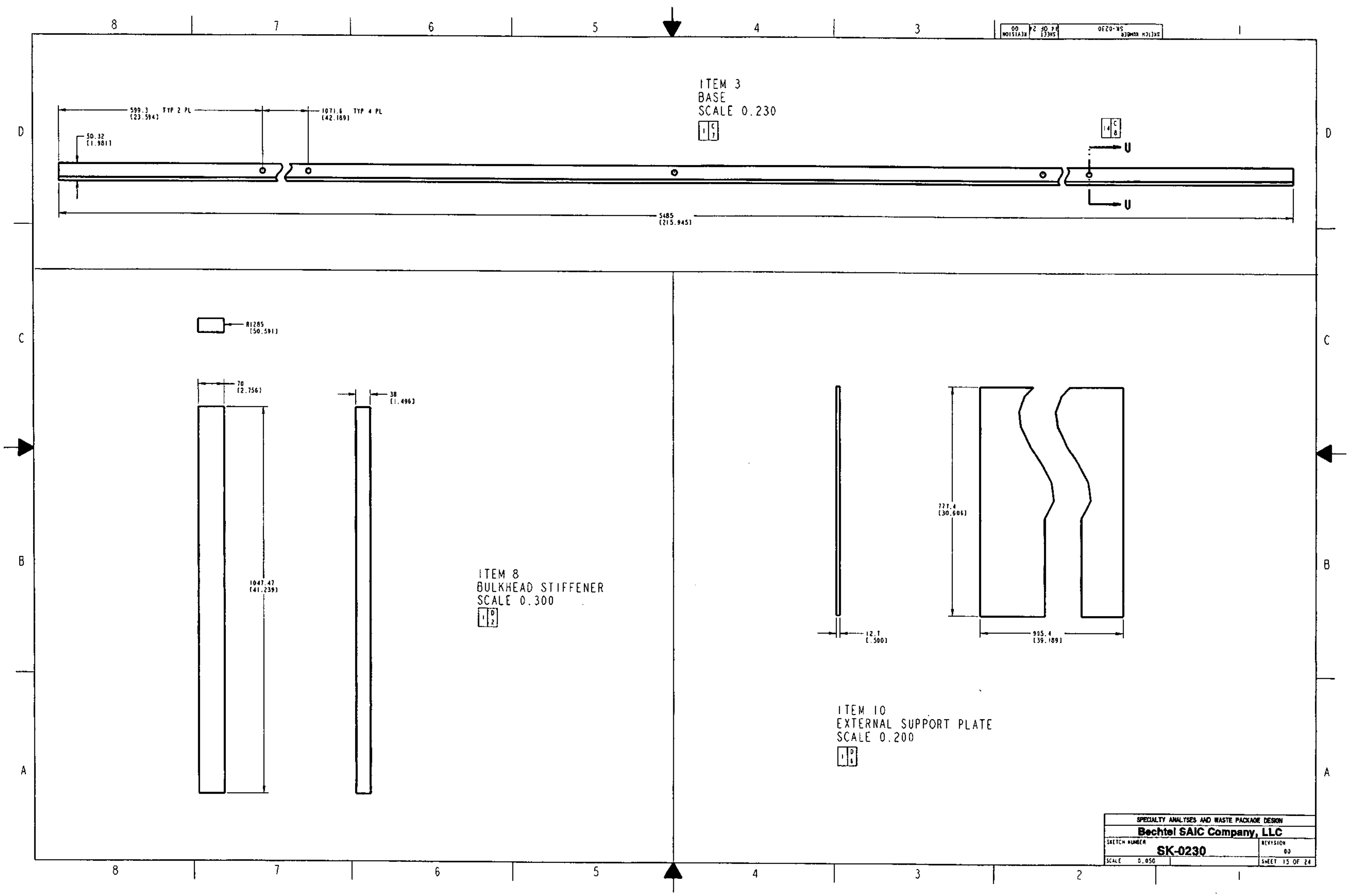

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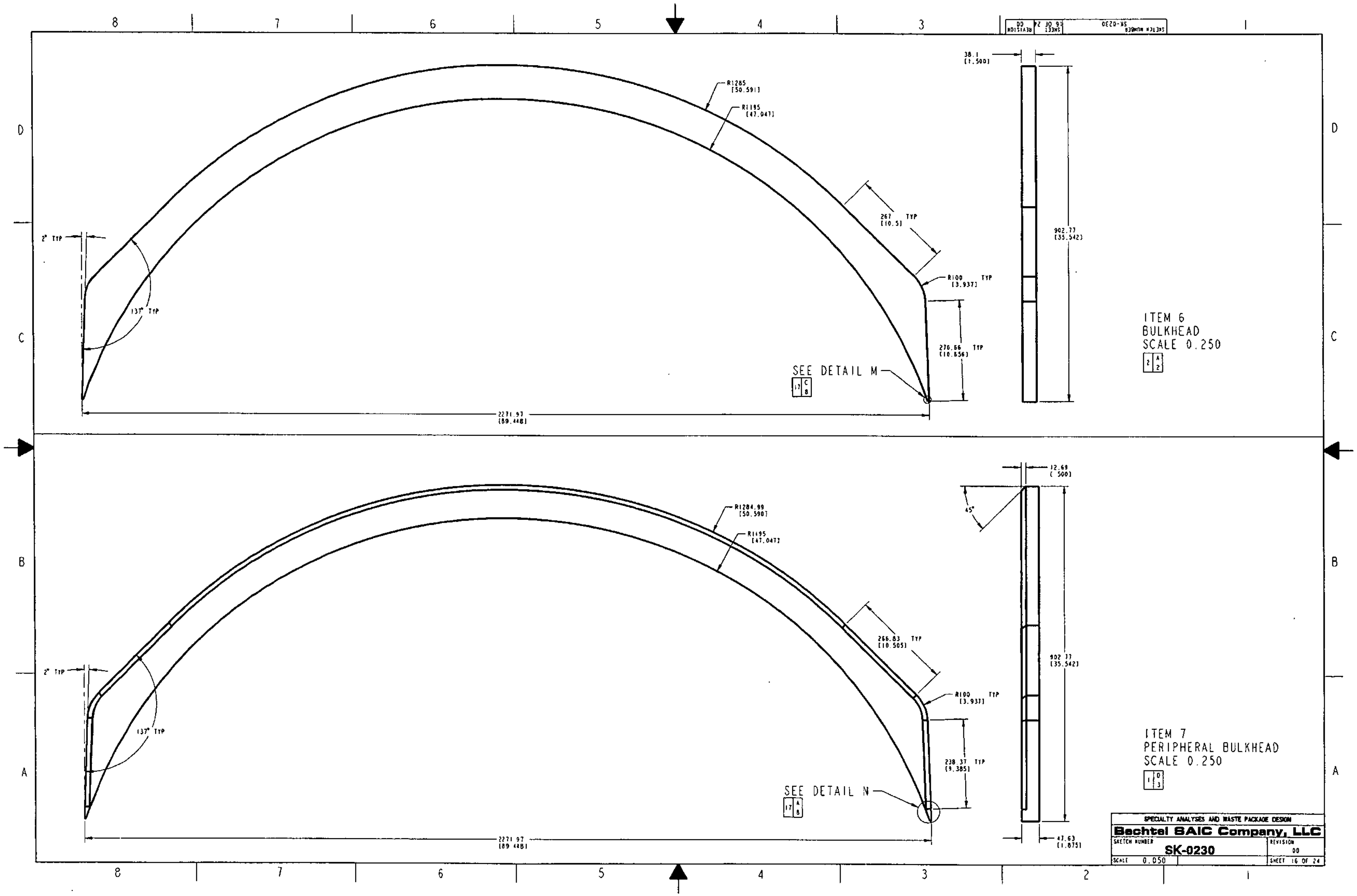

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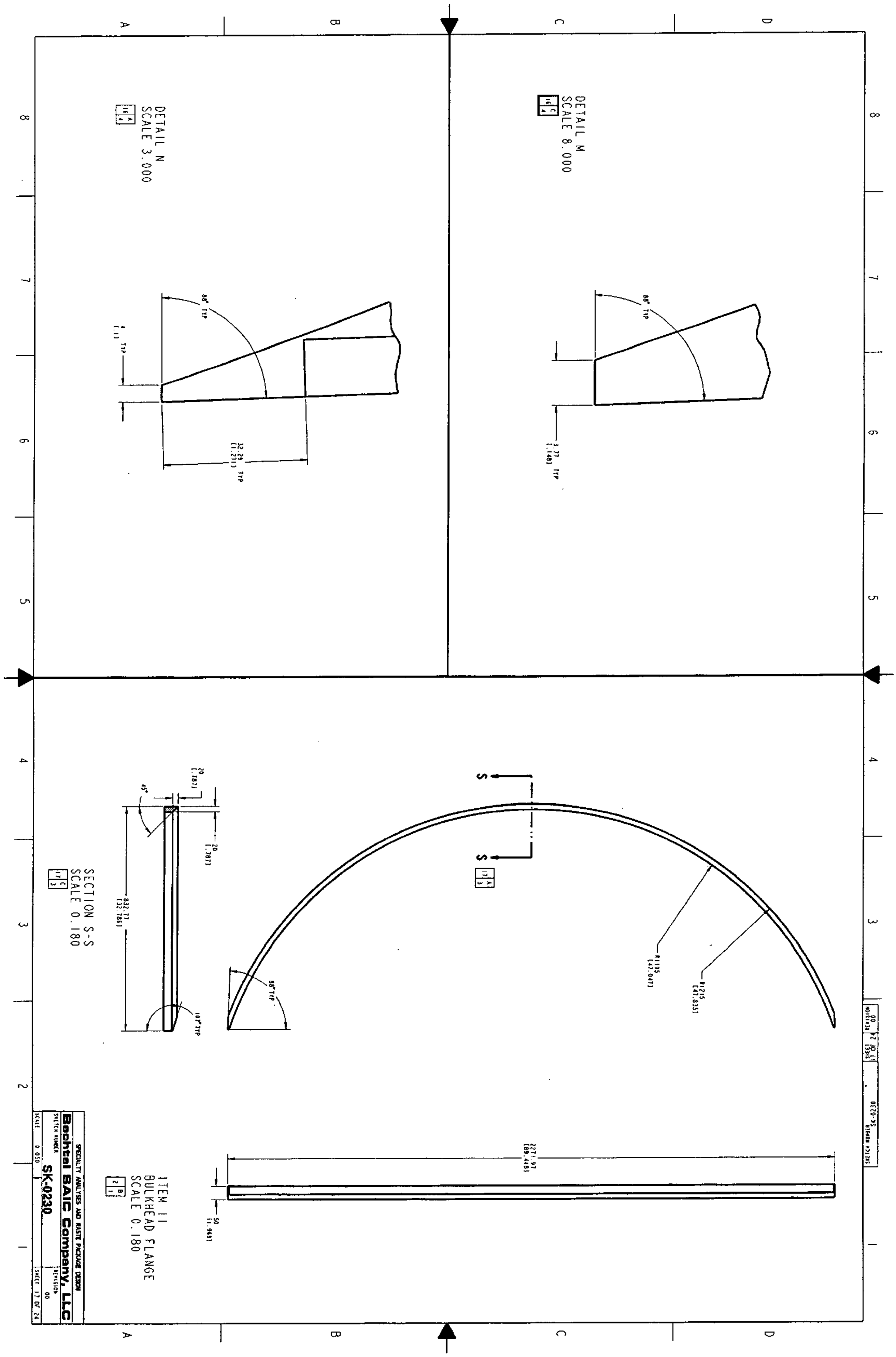

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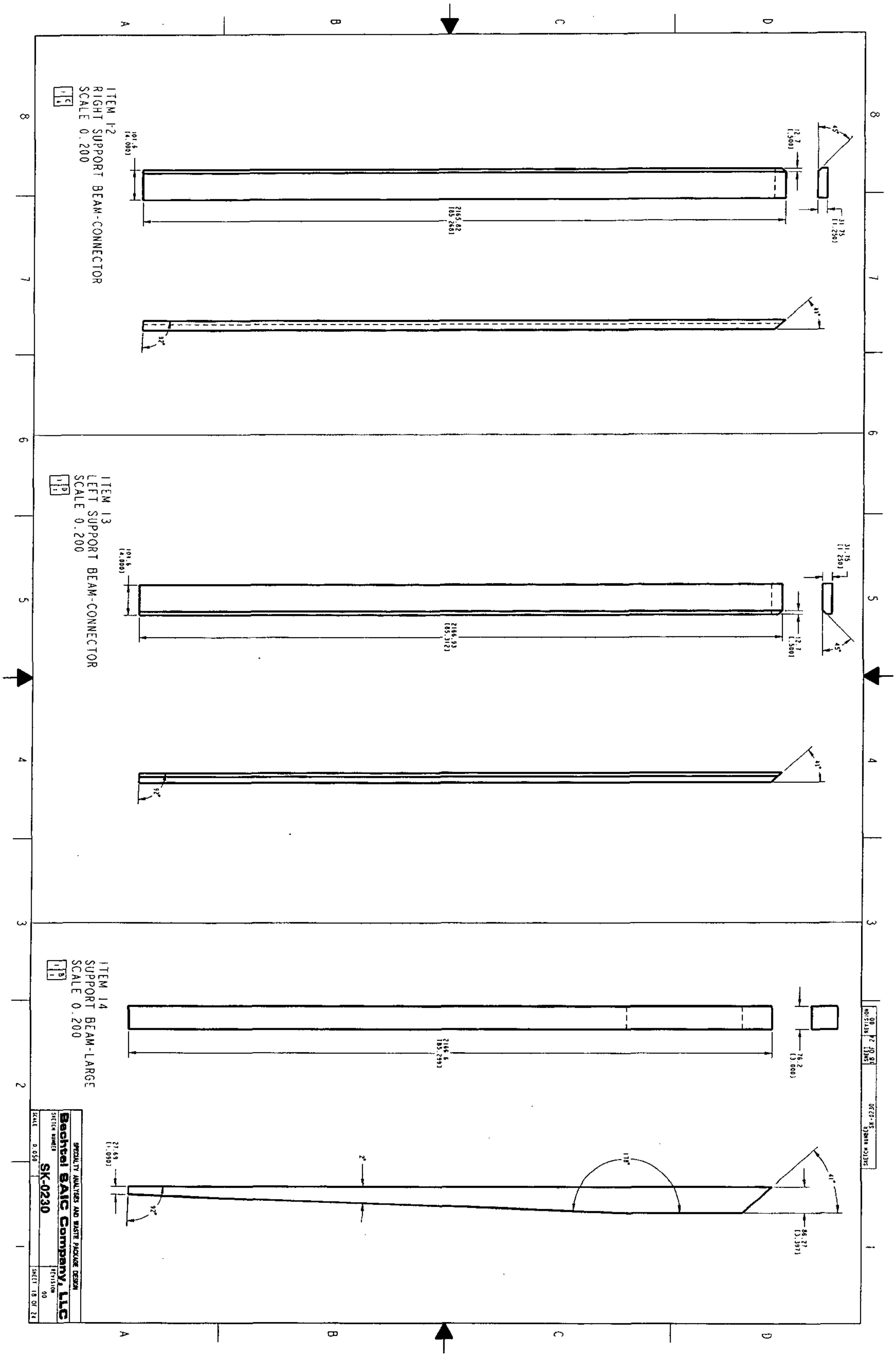

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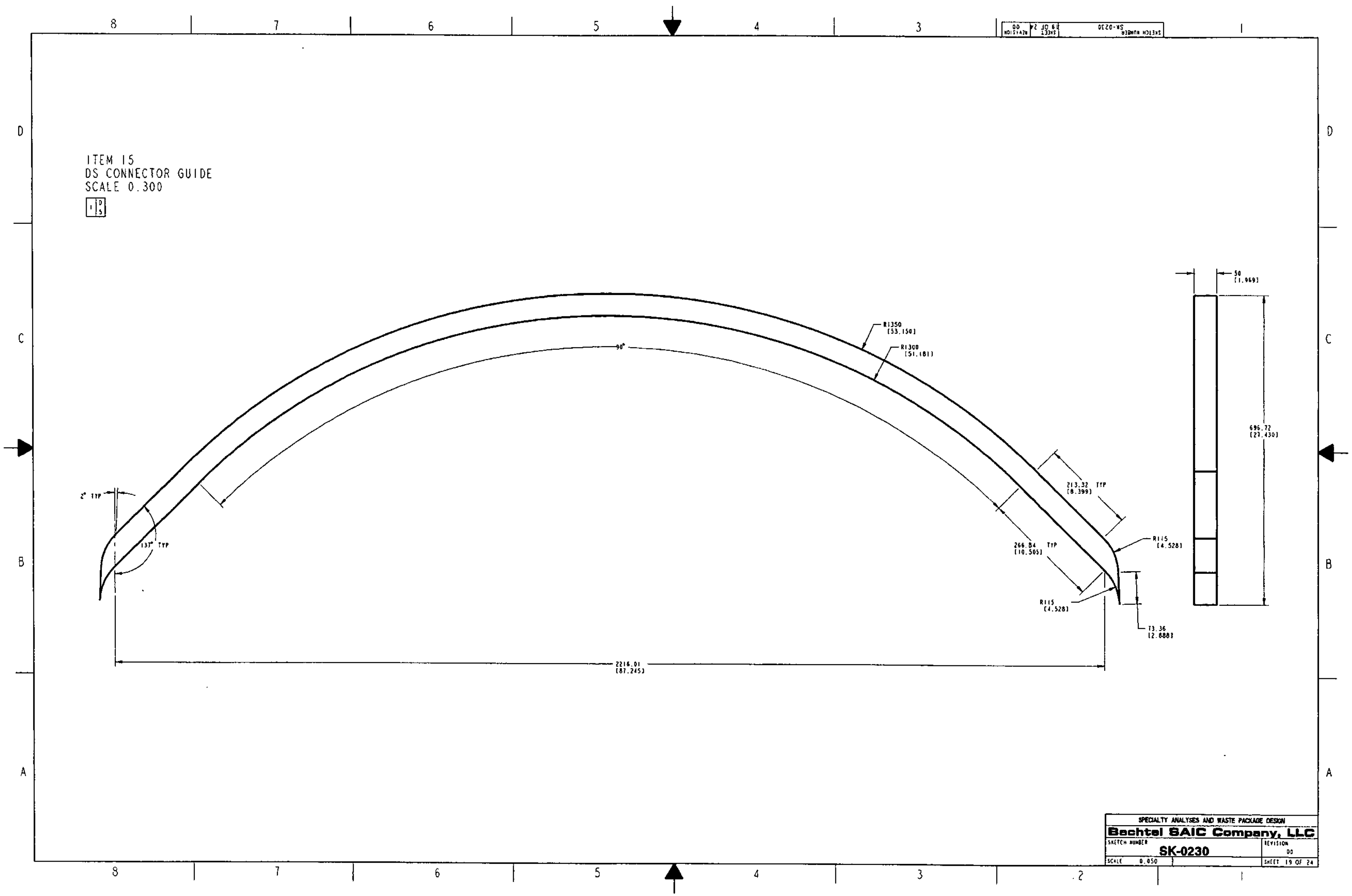

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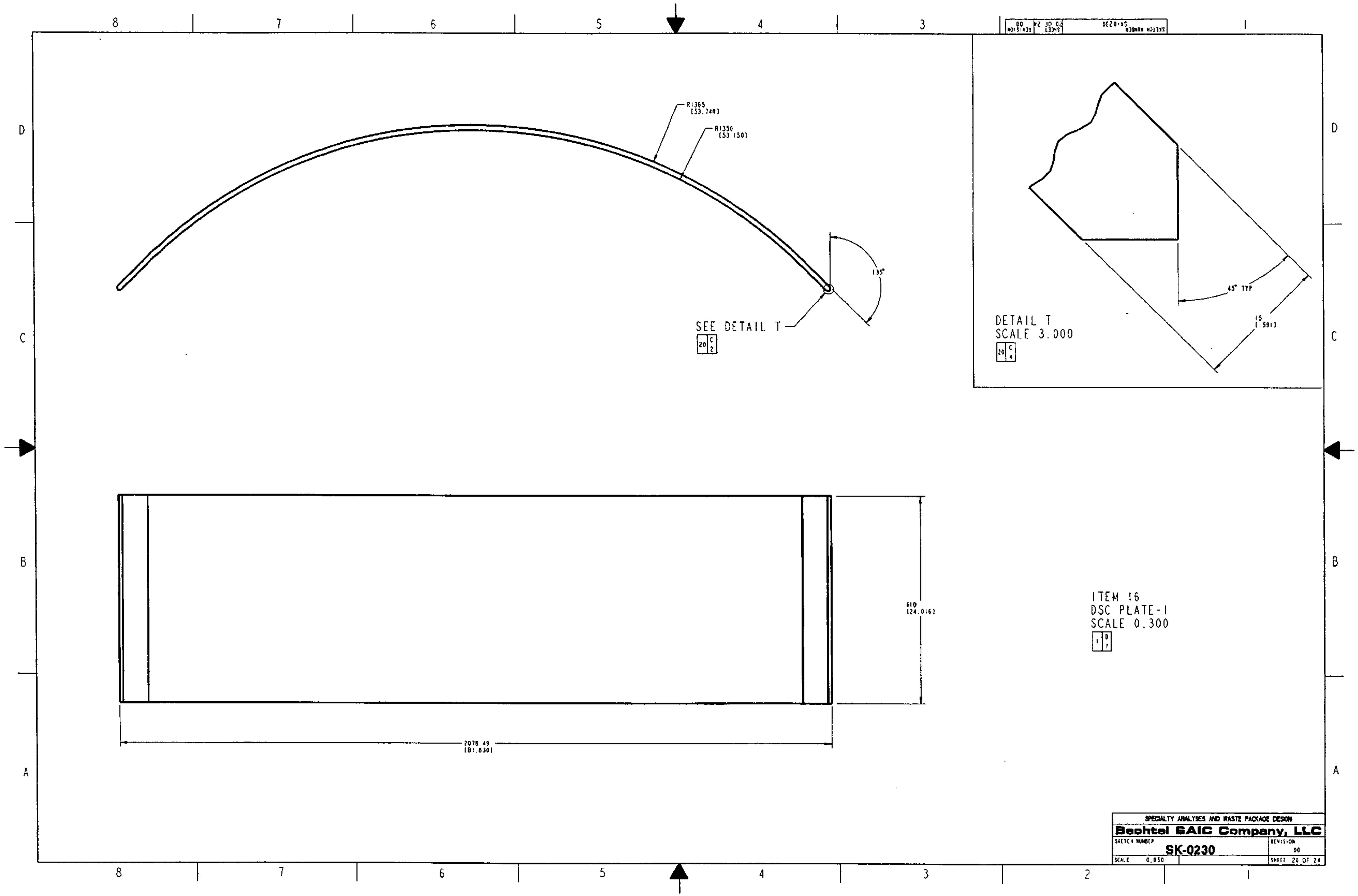

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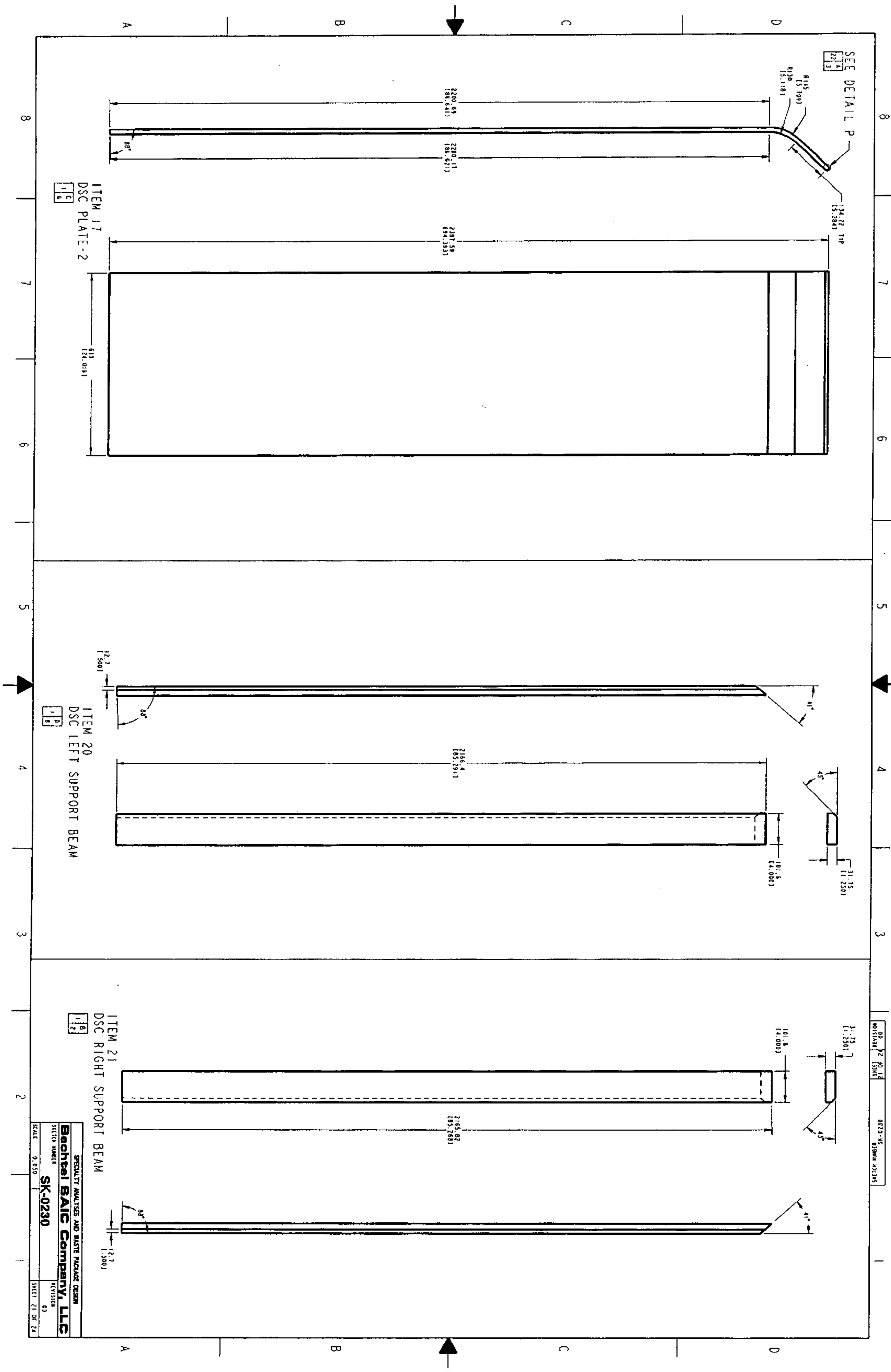

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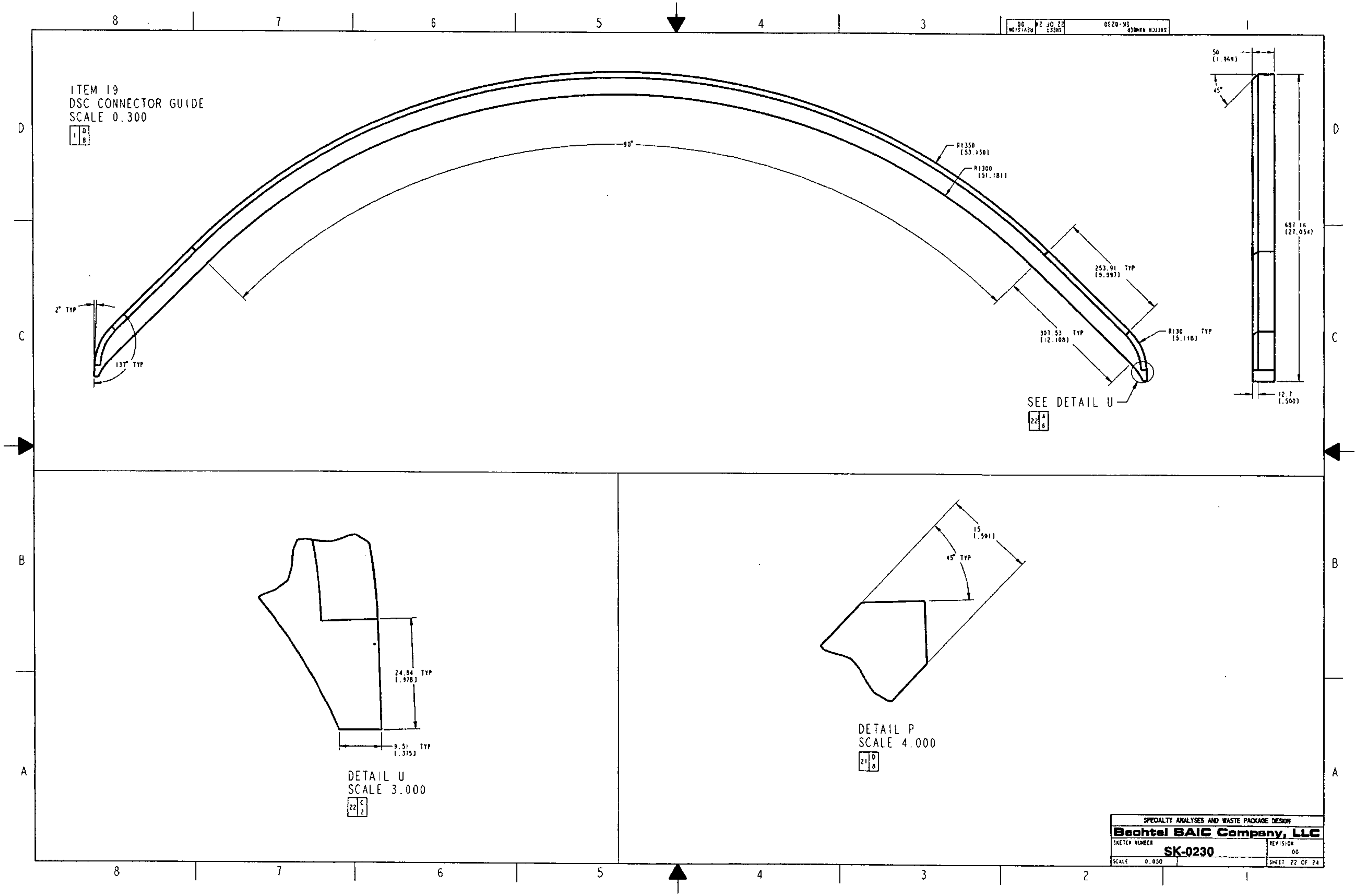

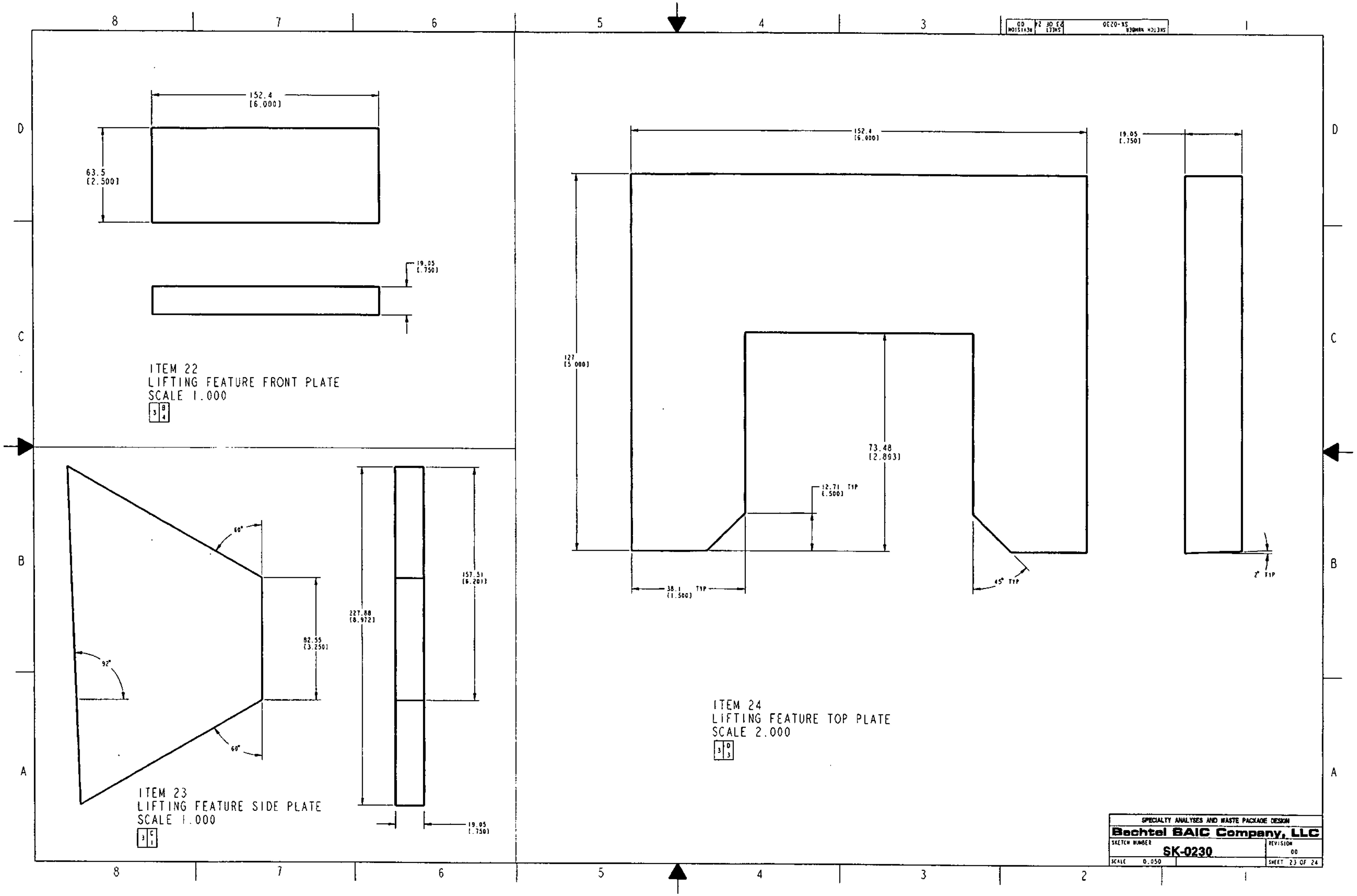
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ITEM 22
LIFTING FEATURE FRONT PLATE
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152.4 [6.000]
63.5 [2.500]
19.05 [.750]
ITEM 23
LIFTING FEATURE SIDE PLATE
SCALE 1.000
60°
92°
82.55 [3.250]
227.88 [8.972]
157.51 [6.201]
19.05 [.750]
ITEM 24
LIFTING FEATURE TOP PLATE
SCALE 2.000
152.4 [6.000]
127 [5.000]
73.48 [2.893]
12.71 TYP [.500]
38.1 TYP [1.500]
45° TYP
19.05 [.750]
2° TYP
SPECIALTY ANALYSES AND WASTE PACKAGE DESIGN
Bechtel BAIC Company, LLC
SKETCH NUMBER SK-0230
REVISION 00
SCALE 0.050
SHEET 23 OF 24

NAME:MCKENZIED2 OBJECT:SK-0230_REV00.24 DATE:06-Nov-02 12:38:57

COMPONENT LIST

ITEM NUMBER	ASSEMBLY	SUBASSEMBLY	COMPONENT NAME	MATERIAL	THICKNESS	MASS (KG)	QTY ROD
-1	SR DRIPSHIELD	-	SR DRIPSHIELD	-	-	5000	1
1	-	-	DS PLATE-1	SB-265 R52400	15	834	1
2	-	-	DS PLATE-2	SB-265 R52400	15	890	2
3	-	-	BASE	SB-575 N06022	10	55	2
4	-	-	STABILIZATION PIN	SB-575 N06022	15	.07	10
5	-	-	STABILIZATION PIN WASHER	SB-575 N06022	5	.03	20
6	-	-	BULKHEAD	SB-265 R56405	38	45	4
7	-	-	PERIPHERAL BULKHEAD	SB-265 R56405	48	55	2
8	-	-	BULKHEAD LONGITUDINAL STIFFENER	SB-265 R56405	38	12	15
9	-	-	INTERNAL SUPPORT PLATE	SB-265 R52400	12.7	16	10
10	-	-	EXTERNAL SUPPORT PLATE	SB-265 R52400	12.7	44	10
11	-	-	BULKHEAD FLANGE	SB-265 R56405	20	10	8
12	-	-	RIGHT SUPPORT BEAM-CONNECTOR	SB-265 R56405	102	30	2
13	-	-	LEFT SUPPORT BEAM-CONNECTOR	SB-265 R56405	102	30	2
14	-	-	SUPPORT BEAM-LARGE	SB-265 R56405	76	45	8
15	-	-	DS CONNECTOR GUIDE	SB-265 R52400	50	29	2
16	-	-	DSC PLATE-1	SB-265 R52400	15	100	1
17	-	-	DSC PLATE-2	SB-265 R52400	15	101	2
18	-	-	NOT USED	-	-	-	-
19	-	-	DSC CONNECTOR GUIDE	SB-265 R52400	50	30	2
20	-	-	DSC LEFT SUPPORT BEAM	SB-265 R56405	102	30	1
21	-	-	DSC RIGHT SUPPORT BEAM	SB-265 R56405	102	30	1
-2	-	LIFTING FEATURE ASSEMBLY	-	-	-		4
22	-	-	LIFTING FEATURE FRONT PLATE	SB-265 R56405	19.1	.82	4
23	-	-	LIFTING FEATURE SIDE PLATE	SB-265 R56405	19.1	1.7	8
24	-	-	LIFTING FEATURE TOP PLATE	SB-265 R56405	19.1	1.1	4
-	-	-	TOTAL TITANIUM GRADE 7 WELDS	SFA-5.16 R52401	-	110	-

WELD LIST

WELD NUMBER	MATERIAL	MASS (KG)	QTY ROD
1	SFA-5.16 R52401	1.4	4
2	SFA-5.16 R52401	.006	20
3	SFA-5.16 R52401	.892	10
4	SFA-5.16 R52401	.004	8
5	SFA-5.16 R52401	.005	4
6	SFA-5.16 R52401	1.2	2
7	SFA-5.16 R52401	2.6	8
8	SFA-5.16 R52401	.380	10
9	SFA-5.16 R52401	.366	10
10	SFA-5.16 R52401	097	20
11	SFA-5.16 R52401	.362	10
12	SFA-5.16 R52401	.377	10
13	SFA-5.16 R52401	.276	10
14	SFA-5.16 R52401	.276	10
15	SFA-5.16 R52401	.420	30
16	SFA-5.16 R52401	.786	2
17	SFA-5.16 R52401	.614	2
18	SFA-5.16 R52401	.614	2
19	SFA-5.16 R52401	786	2
20	NOT USED	-	-
21	NOT USED	-	-
22	SFA-5.16 R52401	.614	8
23	SFA-5.16 R52401	.614	8
24	NOT USED	-	-
25	SFA-5.16 R52401	.930	4
26	SFA-5.16 R52401	.155	4
27	SFA-5.16 R52401	.168	2
28	SFA-5.16 R52401	1.0	4
29	SFA-5.16 R52401	034	4
30	SFA-5.16 R52401	.777	1
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34	SFA-5.16 R52401	1.0	1
35	SFA-5.16 R52401	.777	1
36	SFA-5.16 R52401	.777	1
37	SFA-5.16 R52401	013	8
38	SFA-5.16 R52401	.030	4
39	SFA-5.16 R52401	.020	8
40	SFA-5.16 R52401	.025	8
41	SFA-5.16 R52401	.007	8
42	SFA-5.16 R52401	.014	8
43	SFA-5.16 R52401	.043	4
44	SFA-5.16 R52401	046	8
TOTAL TITANIUM GRADE 7 WELDS	SFA-5.16 R52401	110	-

SPECIALTY ANALYSES AND WASTE PACKAGE DESIGN
Bechtel SAIC Company, LLC
SKETCH NUMBER SK-0230 REVISION 00
SCALE 0.050 SHEET 24 OF 24

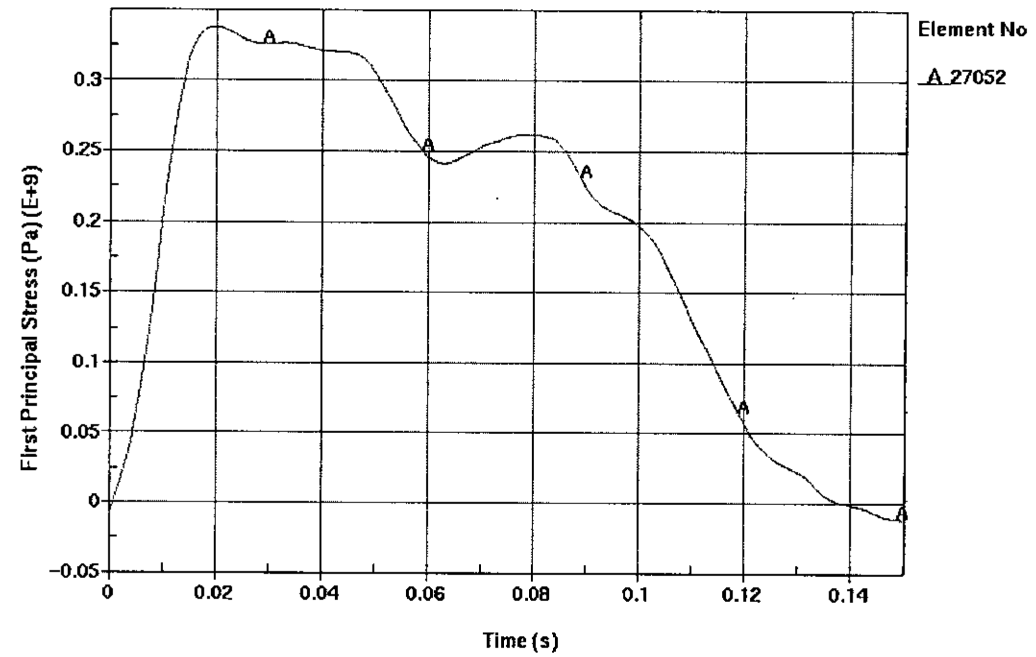

Figure II-1. First Principal Stress for Element #27052. Maximum Peak Value in DS Top Plate. 14.5 MT Vertical Rock Fall Mesh Sensitivity Case with 5 Elements Through the Shell Thickness

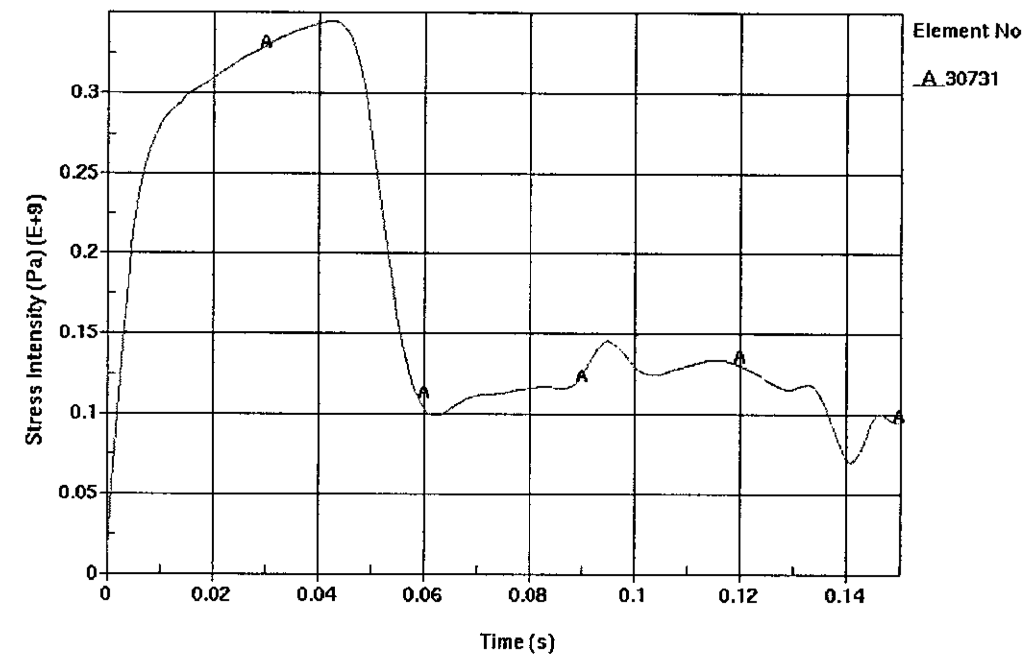

Figure II-2. Stress Intensity for Element #30731. Maximum Peak Value in DS Top Plate. 14.5 MT Vertical Rock Fall Mesh Sensitivity Case with 5 Elements Through the Shell Thickness

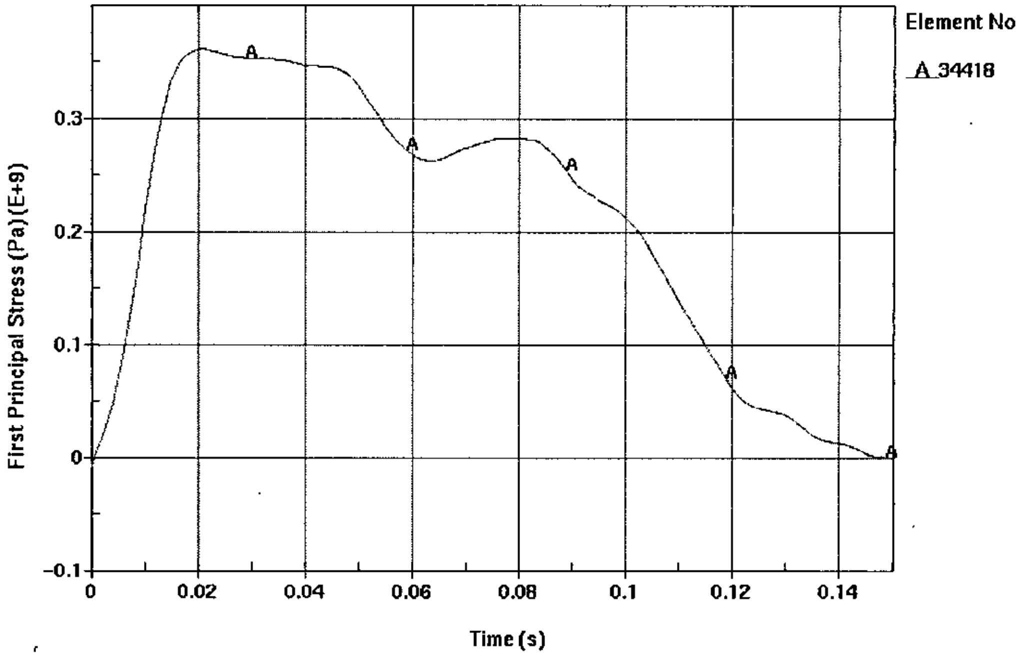

Figure II-3. First Principal Stress for Element #34418. Maximum Peak Value in DS Top Plate. 14.5 MT Vertical Rock Fall Mesh Sensitivity Case with 6 Elements Through the Shell Thickness

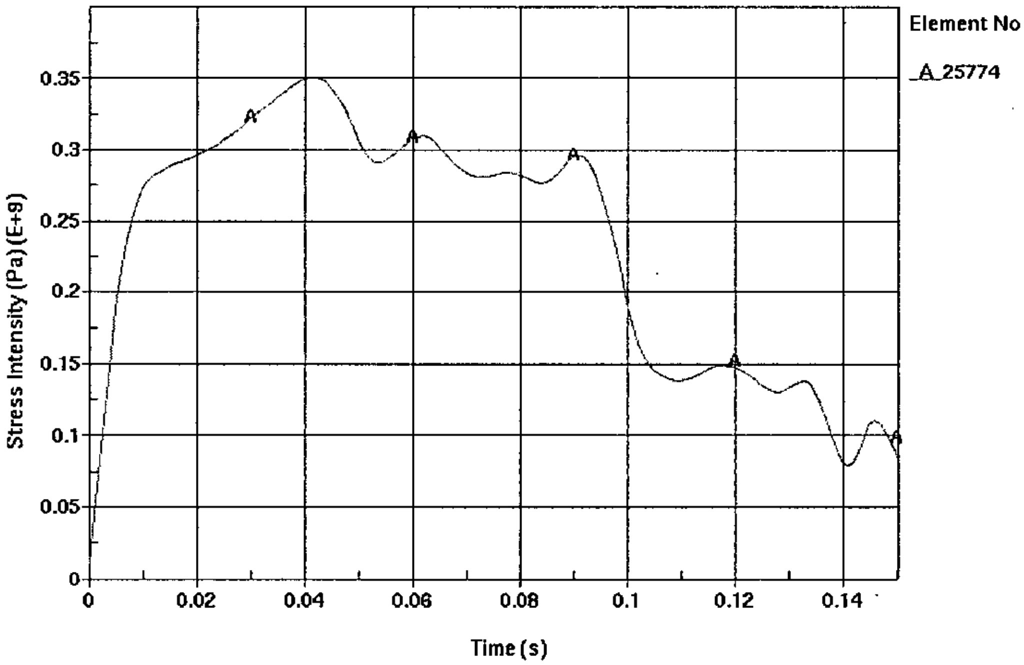

Figure II-4. Stress Intensity for Element #25774. Maximum Peak Value in DS Top Plate. 14.5 MT Vertical Rock Fall Mesh Sensitivity Case with 6 Elements Through the Shell Thickness

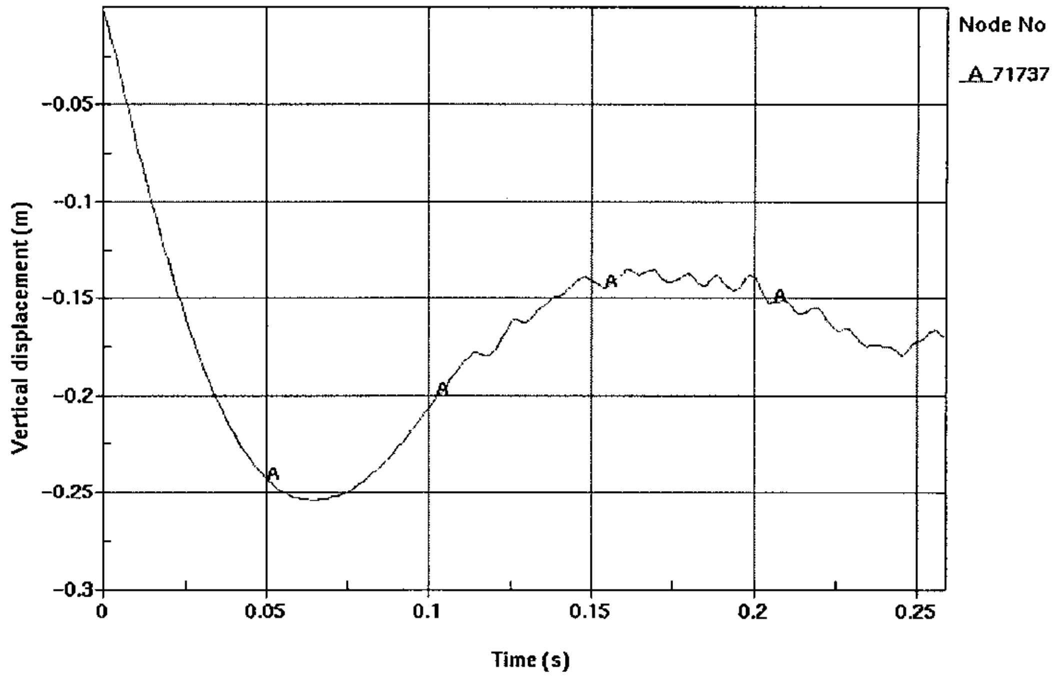

Figure II-5. Vertical Displacement for Element #71737. Maximum Peak Value in DS longitudinal stiffener. 11.5 MT Vertical Rock Fall for 10^{-7} Ground Motion

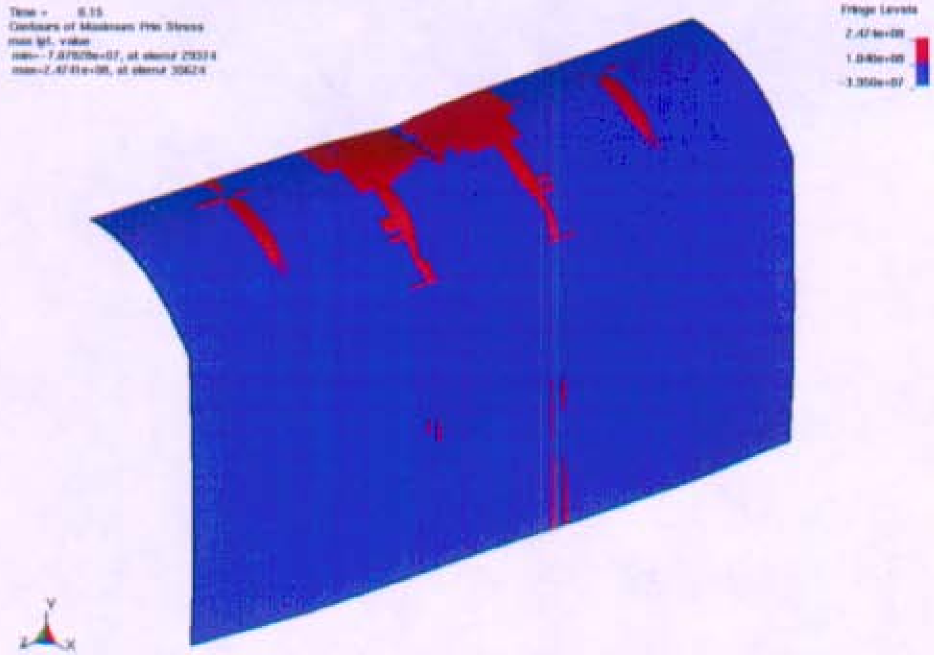

Figure II-6. Typical First Principal Residual Stress (Pa) Distribution on DS Plates (14.5 MT Vertical Rock Fall)

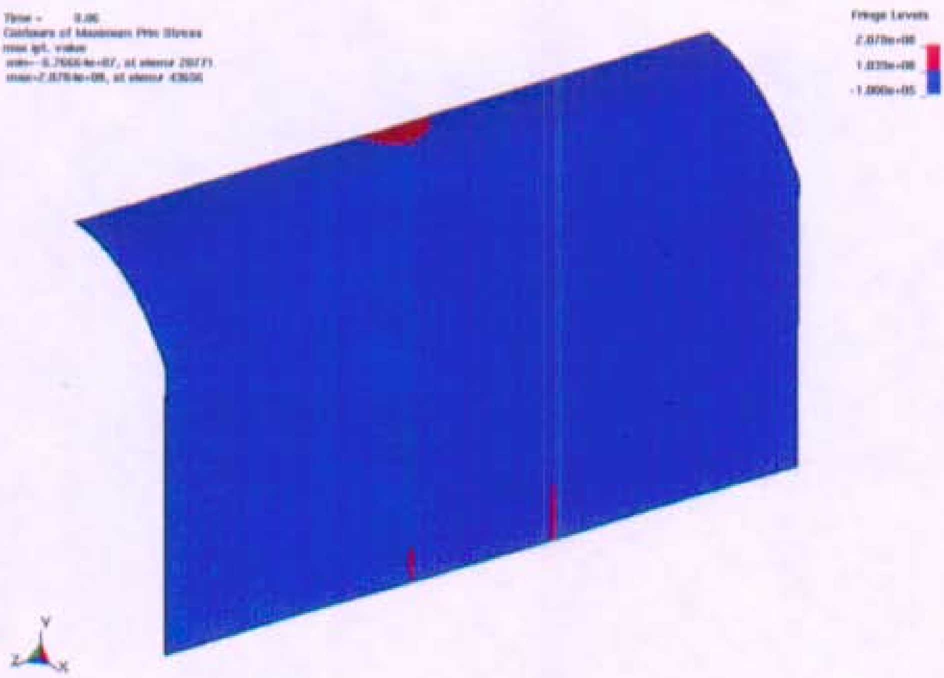

Figure II-7. Typical First Principal Residual Stress (Pa) Distribution on DS Plates (3.3 MT Vertical Rock Fall)