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DESIGN CONSIDERATIONS FOR CRBRP HEAT TRANSPORT SYSTEM PIPING OPERATING AT ELEVATED TEMPERATURES

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ABSTRACT

The heat transport system sodium piping for the Clinch River Breeder Reactor Plant (CRBRP) within the reactor containment building must withstand high temperatures for long periods of time. Each phase of the mechanical design process of the piping system is influenced by elevated temperature considerations which include material thermal creep effects, ratchetting caused by rapid temperature transients and stress relaxation, and material degradation effects. This requires that careful attention be given to through-wall temperature gradients and time-dependent material behavior in the design and analysis process. This paper describes the structural design philosophy and approach taken to design the CRBRP piping operating in a high temperature environment. The resulting design of the heat transport system piping is presented along with a discussion of special features that resulted from the elevated temperature considerations.

INTRODUCTION

The heat transport system sodium piping for the Clinch River Breeder Reactor Plant (CRBRP) within the reactor containment building must withstand high temperatures for long periods of time, in the presence of flowing sodium, and with a variety of thermal transients superposed during the plant life. The reactor primary outlet piping operates at temperatures as high as 546°C (1015°F) for a significant portion of the 30-year operating life of the plant. The primary cold leg sodium piping (i.e., the reactor inlet) operates at a temperature of 399°C (750°F), but for some transients the temperature of the cold leg reaches 538°C (1000°F).

Each phase of the mechanical design process of the CRBRP heat transport system piping was influenced by elevated temperature considerations. Because the piping operates at temperatures greater than 427°C (800°F), time-dependent material failure modes as well as time-independent material failure modes must be accounted for in the design. Rapid temperature excursions or transients which occur in the CRBRP heat transport piping may induce through-wall stresses in the pipe wall in excess of the material yield strength causing local plastic straining which can contribute to a ratchet mechanism. Also, the high temperature flowing sodium in austenitic stainless steel piping may result in varying degrees of interstitial mass transfer and other material degradation effects.

The purpose of this paper is to describe in detail the design of the CRBRP primary heat transport system piping that resulted from the consideration of system design requirements and the elevated temperature environment.

DESIGN REQUIREMENTS, GUIDELINES AND METHODS

General Requirements

The specific design requirements for the HTS piping system were stipulated in the design specification. These requirements were established to be consistent with the performance of specific functions by the piping system during reactor operation and with quality and safety standards developed by regulatory and industry bodies for the design and fabrication of nuclear components. In line with these requirements, the CRBRP heat transport piping system is designed and analyzed as an ASME Class 1, Seismic Category I[1] nuclear component in accordance with the requirements of the ASME B&PV Code, Section III[2] supplemented by special provisions given in ASME Code Case 1592-7[3] and certain RDT Standards[4,5] for nuclear components in elevated temperature service. The consideration of thermal creep effects sets the elevated temperature rules of Code Case 1592-7 apart from the ASME Code Section III, Subsection NB rules. Unlike Subsection NB design rules which basically guard against time-independent failure modes, the elevated temperature rules are applicable for service conditions where creep and relaxation effects are significant. Therefore, the elevated temperature rules require that the mechanical design of the CRBRP piping system account for time-dependent as well as time-independent material properties.

The design specification provides the applied loadings that are used in the CRBRP piping design and evaluation. These loadings include such effects as internal pressure, deadweight, anchor motions, thermal expansion, thermal transients and seismic excitations.

Arrangement and Support System Design Guidelines

From the operational, functional, and structural requirements listed in the design specification, specific guidelines were established for use in the development of the piping system arrangement and layout and for the design of the support and restraint system for the piping. These guidelines were established from radiation protection, maintenance, inservice inspection, safety and high temperature considerations and from the general characteristics of the reactor containment building.

The arrangement of the CRBRP heat transport system piping was developed using the following guidelines:

1. piping had to be elevated or contained in guard tanks
2. routing had to preclude neutron shine on components, particularly the intermediate heat exchanger(IHX)
3. the piping had to be arranged in three essentially identical heat transport loops from the reactor in separate cells
4. the primary loop pump had to be located in the hot portion of the loop
5. high point vents had to be provided in both the hot leg and cold leg piping
6. the piping had to be drainable
7. the piping had to be trace heated and insulated with the piping providing the support for these items
8. installation of and access to the piping had to be practical (approximately one meter clearance between the piping and building walls and components had to be provided)

9. the piping loops had to accommodate the system thermal expansion
10. all connections between piping components had to be welded
11. bellows seals attached to the piping had to be provided between the reactor cavity and heat transport system cells
12. rigid seals attached to the piping had to be provided at the reactor containment building boundary
13. stresses in the piping were to be limited to the established screening limits.

As part of producing the general arrangement of the piping system, the task of establishing the location, type, size, and arrangement of the pipe supports is an integral part of the design process. In this way the piping, its supporting systems, and their combined interaction with the other heat transport system components and building structures are subjected to study. The guidelines established from piping design and functional requirements for the supports and restraints of the piping system were as follows:

1. pipe support had to be provided by non-integral attachments, insulated from the pipe wall
2. load bearing insulation had to transmit piping loads to the non-integral attachment (or clamp)
3. pipe supports had to be primarily of the constant load type
4. pipe seismic restraints (or snubbers) had to be of the mechanical type and generally located at support locations
5. maximum span of piping between supports had to be based on a deadweight bending stress of 10.3 MPa (1500 psi) and/or supports had to be located at points of concentrated loads
6. maximum span at curved sections of pipe had to be limited to 75% of the straight run span
7. the span for seismic restraints (or snubbers) had to be consistent with the screening stress limits

The guidelines described above for developing the arrangement and support system for the piping coupled with the screening or pipe routing rules provided a basis for assessing the relative merit of alternative sizes, arrangements and supports of the piping system. This iterative design process lead to an acceptable mechanical design of the CRBRP heat transport system piping.

Pipe Routing (Screening) Rules

Pipe routing or screening rules that account for elevated temperature considerations were established for assessing the acceptability of the many alternative arrangements of the CRBRP piping and its support system that were considered in the design process. The objective of the screening rules is to establish stress limits appropriate to each type of loading such that, in the final detailed stress evaluation of the piping, the ASME Code design limits for combined loadings are satisfied.

A wide spectrum of structural analysis methods may be used to show compliance with the ASME Code limits. At one end of the spectrum the analytical effort is very small and the piping design is characterized by relatively long loops and many supports. At the other end of the spectrum the analytical effort may be very large and the piping design may be characterized by a relatively compact arrangement and fewer supports. Optimum pipe routing rules must contribute to a minimum total cost.

It is helpful if the piping analysis for deadweight, thermal expansion and seismic loads can be carried out independently of each other during the design process. The allowable stress in the pipe is apportioned to each different load source so that the combined stresses do not exceed the allowable ASME Code stress limits. With separate and distinct load and stress limits for each of the major load sources, the analysis for each can be carried out independently. This will assure that if the stress limits are satisfied for the individual loadings they will also be satisfied for the combined loadings.

These load and stress limits, whether applied to load combinations or individual loadings, are generally referred to as "screening rules". In various forms, they have been found to be an excellent aid in the piping design cycle because they permit the piping design to proceed for each type of loading independently without direct consideration of combined load effects.

In conjunction with screening or pipe routing rules, methods for determining piping nozzle loads must be established by the piping designer using a consistent basis with the screening rules to assure that the piping design does not give reactions greater than the specified nozzle loads. Therefore, a method was developed to obtain pipe nozzle loads that gave a practical bound on the expected pipe reactions based upon the limit loads for the piping adjacent to a component nozzle.

To minimize the size of the reactor containment building it is essential that the heat transport piping system loops be short for a compact arrangement. Therefore, the pipe routing rules established for CRBRP piping set relatively high allowable stress limits, recognizing that final ASME Code compliance evaluations could require complex inelastic analysis at a limited number of locations in the piping loops. The pipe routing rules were established by apportioning the allowable stress to the different types of loading categories such as pressure, deadweight, seismic and thermal expansion stresses.

For the heat transport system cold leg piping that is normally operating at temperatures less than 427°C (800°F), the pipe routing rules are based upon satisfaction of the primary-plus-secondary stress intensity range limits; i.e., Equation 10 of Subsection NB-3600 of the ASME Code. Specifically, to establish the individual stress intensity limits for each type of loading for routing the cold leg piping, the primary-plus-secondary intensity range for the selected "worst-case" cycle under upset loading conditions had to be satisfied. The governing relation is:

$$[S(P_L+P_b)] + S(Q) \leq 3\ S_m \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where

$[S(P_L+P_b)]$ = the value of the primary membrane plus bending stress intensity range that occurs during the operating cycle being evaluated.

$S(Q)$ = the value of the secondary stress intensity range that occurs during the operating cycle being evaluated.

S_m = maximum allowable stress for the material from Table I-1.0 of the ASME Code, Section III.

Equation 1 had to be satisfied for a reference cycle which consists of ranges of pressure, OBE, thermal transient and thermal expansion loading. Based upon evaluation of this reference cycle, the pipe routing rules were obtained as a set of allowable stress intensity limits for each of the types of loading considered.

For the heat transport system hot leg piping that is normally operating at temperatures greater than 427°C (800°F) and designed in accordance with Code Case 1592, the elastic stress limits to preclude strain ratchetting are usually the most difficult to satisfy. If elastic analysis is to be used, ratchetting can be precluded by limiting the primary-plus-secondary stress intensity induced under operating conditions involving combined weight, pressure, seismic, thermal expansion and thermal transient loadings. For the purpose of establishing individual stress intensity limits for routing the hot leg piping, the same basic approach used for the cold leg piping was used.

To establish the stress limit for thermal expansion stress, the primary-plus-secondary stress intensity limits to satisfy Equation 1, Paragraph T-1322 of Code Case 1592 (based on elastically calculated stresses), are used. The operating cycle was defined as the ambient heatup-to-normal operating cycle. In equation form the limit as prescribed by the Code Case can be written as follows:

$$[S(P_L+P_b)]_{max} + [S\ (Q)]_{range} \leq 0.90\ (S_a) \quad \ldots \quad (2)$$

where

$[S(P_L+P_b)]_{max}$ = the maximum value of the primary membrane plus bending stress intensity during the cycle.

$[S(Q)]_{range}$ = the maximum value of the secondary stress intensity range during the cycle.

S_a = S_a is equal to S_y if the average wall temperature at one of the stress extremes defining the secondary stress range is below the creep regime. Otherwise, S_a is defined as the lesser of S_y or 1.25 S_t taken at the highest average wall temperature occurring during the cycle at 10^4 hours.

S_y = The average of the minimum specified yield strength values at the maximum and minimum wall averaged temperatures of the cycle under consideration.

S_t = Time dependent material allowable defined in Code Case 1592.

In establishing the thermal expansion stress limit, it should be noted that the loading cycle being evaluated in accordance with Equation 2 does not give the maximum primary-plus-secondary stress which occurs during all normal and upset operating conditions. The OBE seismic upset cycle would probably give the maximum stresses. The use of a cycle which gives less than the maximum stress is based upon, firstly, the judgement that if the cycle which gives the highest stresses was used, the space requirements for the piping loops would be unacceptable from the standpoint of reactor containment building size. Secondly, the pipeline stresses that are calculated during the routing studies are based on the conservative, simplified piping analysis approach as defined in NB-3650. By shifting to detailed elastic analysis as defined in NB-3200, satisfaction of the Code Case 1592 elastic limits for all load cycles in most cases should be met. Thirdly, a 90% factor is applied to the S_a allowable for added assurance that the Code limits can be met in most cases with elastic analysis. Finally, if inelastic analyses are needed, it is expected the amount will be limited.

Once the screening rules had been established and with the design guidelines discussed previously, the mechanical design of the piping and its support system could progress to a firm or baseline arrangement. Pressure, deadweight, thermal expansion and seismic analyses were carried out independently for many design alternatives to determine stresses for comparison with the established screening rule limits. When the guidelines discussed in the previous section and the screening limits were satisfied, the piping and support design was acceptable and the baseline design established.

Design Evaluation

Once the baseline design of the CRBR piping had been established, the detailed structural evaluation was made in accordance with the methods outlined in recognized nuclear industry codes and standards, the ASME B&PV Code and the additional, supplemental requirements of the RDT Standards. The evaluation of the heat transport system piping included, flexibility (static and dynamic), stress,and heat transfer analyses. The flexibility analyses carried out on a linear, elastic basis provided forces and moments at selected points along the pipeline. The heat transfer analyses provided thru-the-pipe wall temperature gradients and average pipe temperatures at structural discontinuities. With these analysis data and a prescribed plant duty cycle or loading history, stress evaluations of the pipeline at selected locations were carried out as shown in Figure 1 with the

ELTEMP program[6] at elbow midpoints and circumferential weld joints between an elbow and a straight pipe section.

Initially the stress evaluations were carried out on an elastic basis. At a given location in the pipeline, stresses from the various loadings were combined to determine total primary or load-controlled stresses at a given time in the load history and to find secondary or peak stress (strain-controlled) ranges between times in the histogram. The primary stresses were checked against a restrictive allowable that prevents gross yielding through the pipe wall. Next, the possibility of gross distortion and creep-fatigue were checked using the elastically calculated primary stresses and ranges of secondary and peak stresses.

If the strain-controlled limits are not satisfied on an elastic basis either redesign is necessary or inelastic analyses may be used to show that inelastic strains in the pipeline are not excessive. If the reason for non-compliance of strain-controlled limits is judged to result from excessive thru-the-wall thermal transient stresses, the analysis procedure can be modified to use elastic flexibility analysis (i.e., forces and moments) with an inelastic analysis of the pipe component (i.e., elbow, reducer, etc.) to determine total strains. If the reason for non-compliance is judged to result from excessive flexibility forces due to thermal expansion, the procedure can be modified to use an inelastic flexibility analysis and an elastic or inelastic piping component analysis. An inelastic combined flexibility and component analysis is to be used as a last resort.

DESCRIPTION OF DESIGN

Piping Arrangement

The CRBRP heat transport system is comprised of three piped loops which operate in parallel. Each heat transport loop is subdivided into two systems; a primary heat transport loop and an intermediate heat transport loop which are thermally coupled by an intermediate heat exchanger (IHX). Radioactive sodium is transported by the primary loop from the reactor vessel to the heat exchanger and back to the reactor vessel. Non-radioactive sodium is transported by the intermediate loop (which is located partially in both the reactor containment and steam generator buildings) from the heat exchanger to the steam generators and back. Only the intermediate piping within the reactor containment building will be discussed in this paper. Each of the three primary loops and those sections of the intermediate loops within reactor containment are contained in a separate, shielded and inerted cell in accordance with design requirements.

Certain design requirements and high temperature considerations dictate some distinct features of the mechanical design of heat transport system piping. These requirements and considerations include:

1. the need to maintain system pressure losses at the required flow rates to a reasonable value to conserve pumping powers coupled with low system operating pressure.
2. the corrosive effect of flowing sodium.
3. the high operating temperature, high film coefficient for sodium, large temperature transients and relatively low thermal conductivity of austenitic stainless steel.

Item (1) and (2) above dictate relatively large pipe diameters to minimize sodium velocity. Very low system resistance is especially needed for the piping from the reactor outlet to the primary pump suction to minimize pump NPSH effects at the low operating pressure. Item (2) is best accommodated by the use of austenitic stainless steel. Item (3) dictated the use of thin wall piping to minimize thermal gradients through the pipe wall. The selection of the pipe wall thickness must consider the tradeoff between primary pressure and other load-controlled stresses and secondary thermal transient stresses, the former decreasing with increasing wall thickness and the latter increasing with wall thickness. Based on the key design parameters given in Table 1 for the heat transport system piping and the screening rules that were established to layout the piping loops, a pipe wall thickness of 12.7 mm (0.50 inch) was selected for the entire piping system. Combining all these considerations resulted in the use of 0.61 m (24 inch) O.D. piping with the 12.7 mm (0.50 inch) wall for the incontainment heat transport system except for the reactor outlet piping which is 0.91 m (36 inch) O.D. with the 12.7 mm (0.50 inch) wall. Type 316 stainless steel was used for the hot leg piping material because of its superior high temperature properties, and Type 304 stainless steel was used for the cold leg piping.

The design process to layout the general arrangement of the incontainment piping system was an iterative process based on the arrangement guidelines and pipe routing rules that had been established. Preliminary static piping stress analysis for thermal expansion starts in this basic layout stage. This analysis verified equipment locations (pumps, IHX, check valve , etc.) and the major pipe routing. The following aspects of the piping system were considered in these analyses:

1. heat transport system equipment in the piping system.
2. location and movement of equipment nozzles.
3. method of equipment support.
4. restraint points.
5. interfacing systems including the building.

The general arrangement of the CRBRP heat transport system piping that resulted from the design provess is shown in Figures 2 thru 4. The considerations that played the major role in establishing this layout included (1) the piping had to be elevated above the minimum safe sodium level in the reactor vessel or contained in guard vessels, (2) the need to preclude neutron shine, and (3) the need to provide access. In particular the design shown in the above figures, contains large loops to accommodate thermal expansion, has attached bellow seals between the reactor cavity and heat transport cells, and is rigidly restrained at the reactor containment building penetrations.

Selection of Pipe Support and Restraint Locations

The location, sizing and arrangement of pipe supports is best carried out during the initial study layout and arrangement of the primary and intermediate piping. In this way the piping, its supporting systems, and their combined interaction with other components and building structure can be subjected to study and planning. In addition to establishing the general arrangement of the piping and its support points, early decisions had to be made on the type of supports, their general size, space requirements and access for maintenance, all of which had to be examined in relation to building structures and other related pipe systems.

The design approach used in establishing the location of the piping supports was as follows:

1. In accordance with the guidelines established for locating supports, a reasonable set of locations were selected for pipe supports and seismic restraints.

2. Piping deadweight and seismic flexibility analyses were carried out and, in conjunction with the pipe routing rules, locations of supports and seismic restraints were verified.

3. From step 2, the principal size, arrangement and space requirements for the supports and restraint components were established and the detailed design of the supports and associated hardware such as clamps, rods and bolts could proceed.

Pipe Support System Design

In general, the design approach to provide adequate support and restraint for the large diameter thin wall piping of the CRBRP heat transport system follows the design philosophy of "conventional" piping systems of similar pipe size and wall thickness. There is a great deal of experience in the field in supporting and bracing of pipe lines of this size range and there are many components and accessories readily available as "off the shelf items" which meet ASME Code, Section III requirements that may be used. Many of these shelf items are directly applicable to the support of CRBRP piping; for example, spring supports, constant load hangers and seismic restraints, are all directly applicable. A great many of the accessories such as rods, pads, clevises, etc. are also directly applicable for CRBRP use.

In the design of the support and restraint systems for the CRBRP primary and intermediate piping there are two areas which required special attention and which are departures from the conventional design of pipe supports and restraint systems. These areas are:

1. The selection of seismic restraint types.
2. The design of the pipe clamp, and other support attachments to the pipe wall.

Due to the high radiation level at certain locations along the piping system during normal operation the use of conventional hydraulic snubbers is not recommended because of the reaction of hydraulic fluid and elastomer seals of the units to high levels of radiation. Hydraulic seals tend to become very brittle in the presence of high levels of radiation and thus loose their sealing properties. The liquids tend to gum in high radiation exposure and thus loose their flowing properties so essential to proper operation. In view of this, mechanical snubbers which are essentially unaffected by radiation are used for the CRBRP heat transport system piping within the reactor containment building. Mechanical snubbers [7] have been developed specifically for this type of use and are now widely used in the nuclear power industry.

The design of the pipe clamp and other attachments to the pipe wall presented the second departure from conventional designs. This is brought about by the nature of the liquid metal sodium, which is the heat transport system fluid carried by the piping system. The high, rapid temperature changes, 205°C (400°F), which may occur in the heat transport system and the high film coefficient for sodium may produce high radial temperature gradients and bending stresses in the pipe wall. A metal-to-metal clamp directly applied to the pipe outside diameter or a welded-on attachment would effectively increase the thickness of the pipe locally causing increased stresses in the pipe wall. To avoid this problem for CRBRP piping, non-integral insulated attachments, which are composed of outer rings stood off the piping by an insulating material capable of carrying compressive loads, were used except at pipe anchor points. In addition, the use of insulated clamps minimize pipe heat losses.

The design of the pipe clamp assembly used on horizontal runs of CRBRP piping is shown in Figure 5. The clamp assembly consists of two semi-circular carbon steel rings (with attachment lugs) which are held together by a system of springs to accommodate changes in pipe diameter due to temperature changes. Sandwiched between these rings and the outer pipe wall are two semi-circular load-bearing insulation bands that are 38.1 mm (1.5 inch) thick. These insulation bands contain the load-bearing insulation encased by stainless steel formed and welded sheathing. The springs provide a predetermined clamping load on the pipe wall, while the insulation minimizes the pipe wall thermal transient stress.

At locations where an attachment to the pipe wall is absolutely necessary, such as at the reactor containment building penetrations and at the bellows seals, a specially contoured flued-head design was used. For CRBRP piping, the flued-head piping attachment used is shown in Figure 6. The shape is contoured to limit through-wall thermal transient stresses and material gross discontinuity thermal stresses.

CONCLUSIONS

This paper has provided an overview of the structural design process that was followed in establishing the design of the CRBRP incontainment heat transport system piping which operates in a high temperature environment. The criteria, methods, and procedures being developed in the United States for elevated temperature design have been factored into this design process. In particular, the phases of the mechanical design of the piping system most influenced by elevated temperature considerations were discussed in detail. The resulting design of the CRBRP piping included the use of thin-walled large diameter piping of austenitic stainless steel with a carefully designed non-integral support system because of these elevated temperature considerations.

In conclusion, information exists to design liquid metal fast breeder reactor large diameter piping systems with a high degree of confidence in its integrity.

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TABLE 1

DESIGN PARAMETERS FOR HEAT TRANSPORT SYSTEM (HTS) PIPING

	PHTS Hot Leg	PHTS Crossover	PHTS Cold Leg	IHTS Hot Leg	IHTS Cold Leg
Size	0.91m (36")	0.61m (24")	0.61m	0.61m	0.61m
Material	316 SS	316 SS	304 SS	316 SS	304 SS
Design Temperature	546°C (1015°F)	546°C	413°C (775°F)	518°C (965°F)	413°C
Operat. Temp.	546°C (1015°F)	546°C	399°C (750°F)	518°C	361°F (681°F)
Design Press.	0.21 MPa (30psi)	1.38 MPa (200 psi)	1.38 MPa	2.24MPa (325psi)	2.24 MPa
Operat. Press.	0.04 MPa (6 psi)	1.16 MPa (168 psi)	0.92MPa (133psi)	1.54MPa (224psi)	1.76 MPa (255 psi)

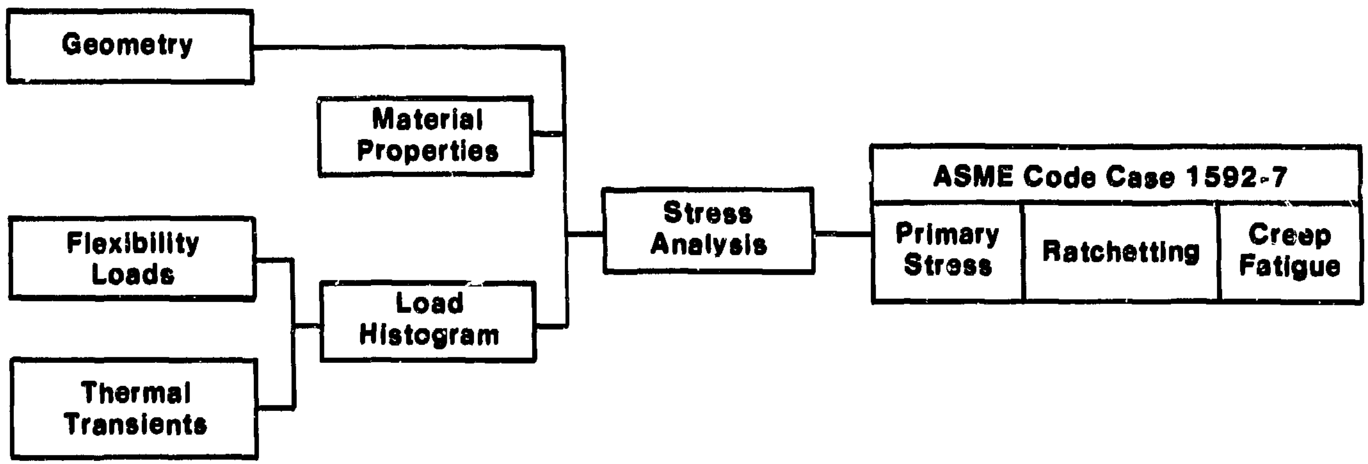

Figure 1. Piping Elastic Analysis Process

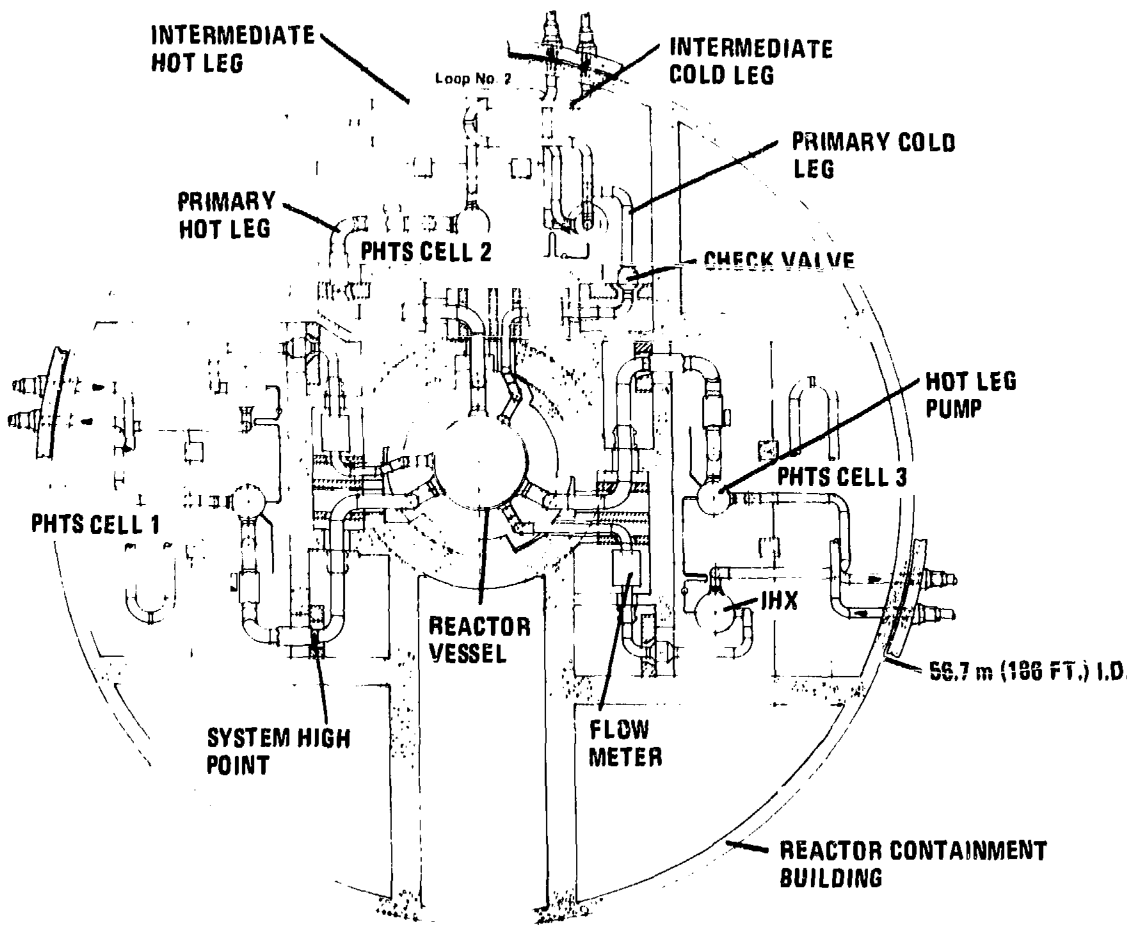

Figure 2. CRBRP Heat Transport System Piping General Arrangement

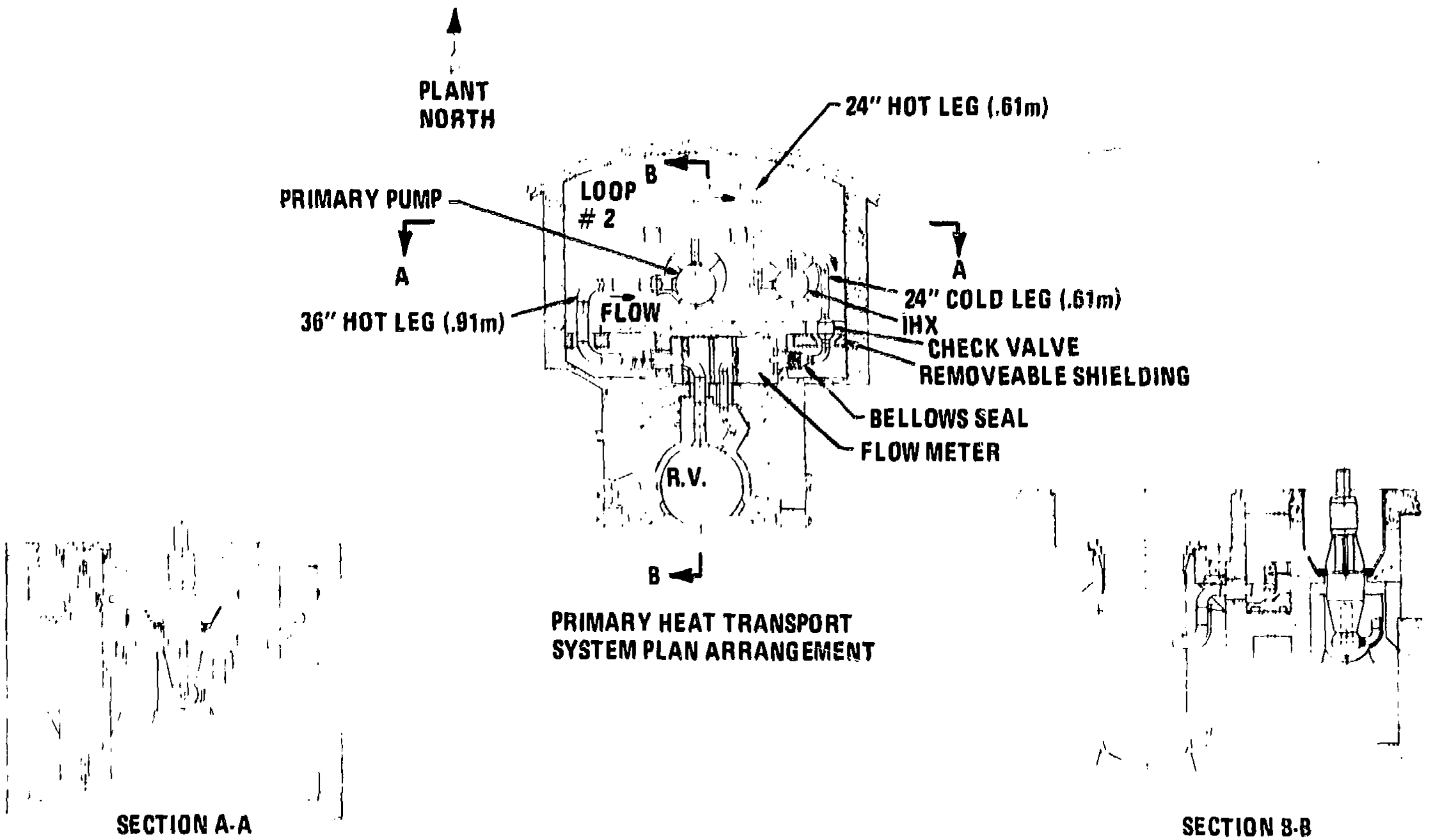

Figure 3. CRBRP Primary Heat Transport System Piping

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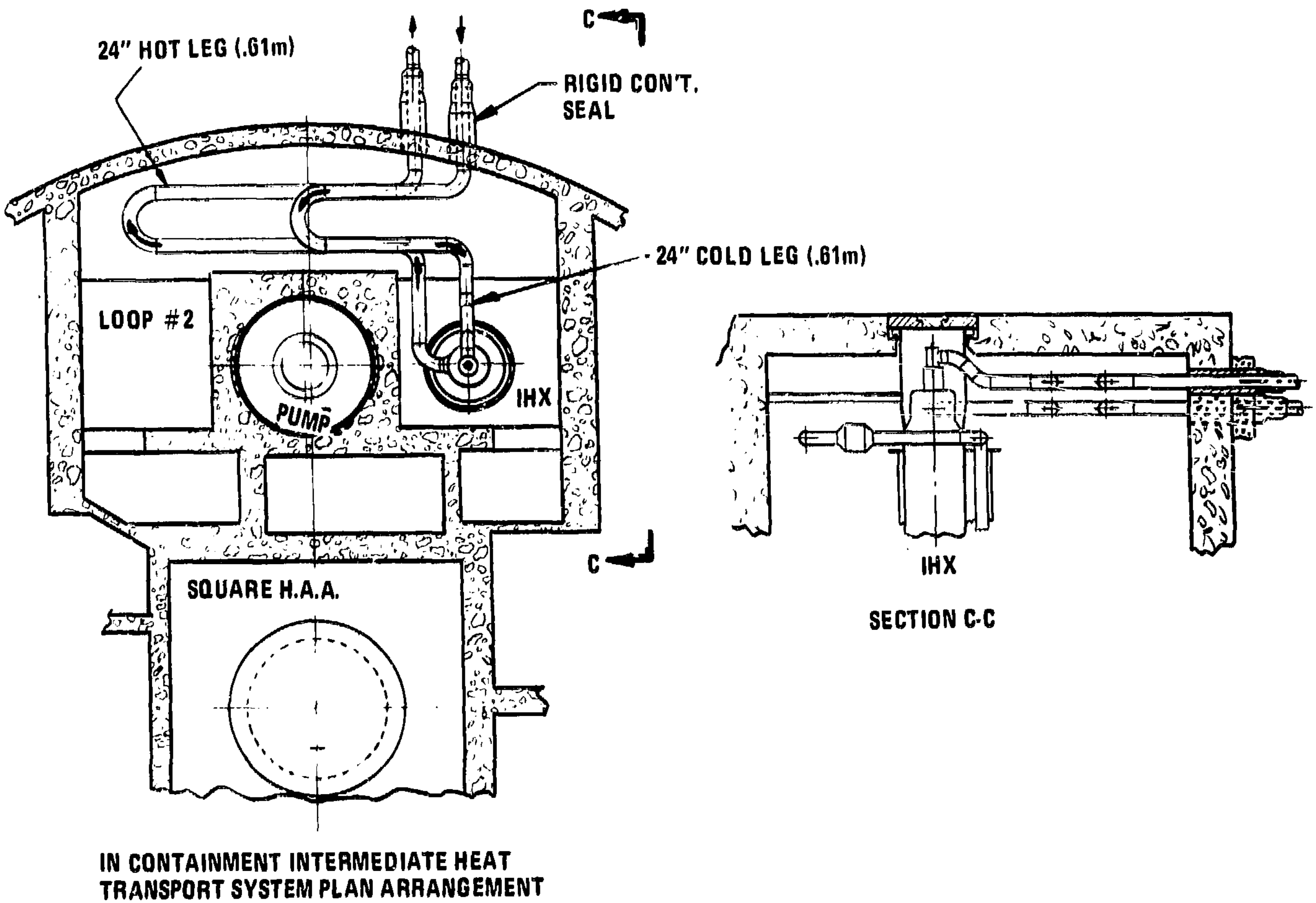

Figure 4. CRBRP Intermediate Heat Transport System Piping

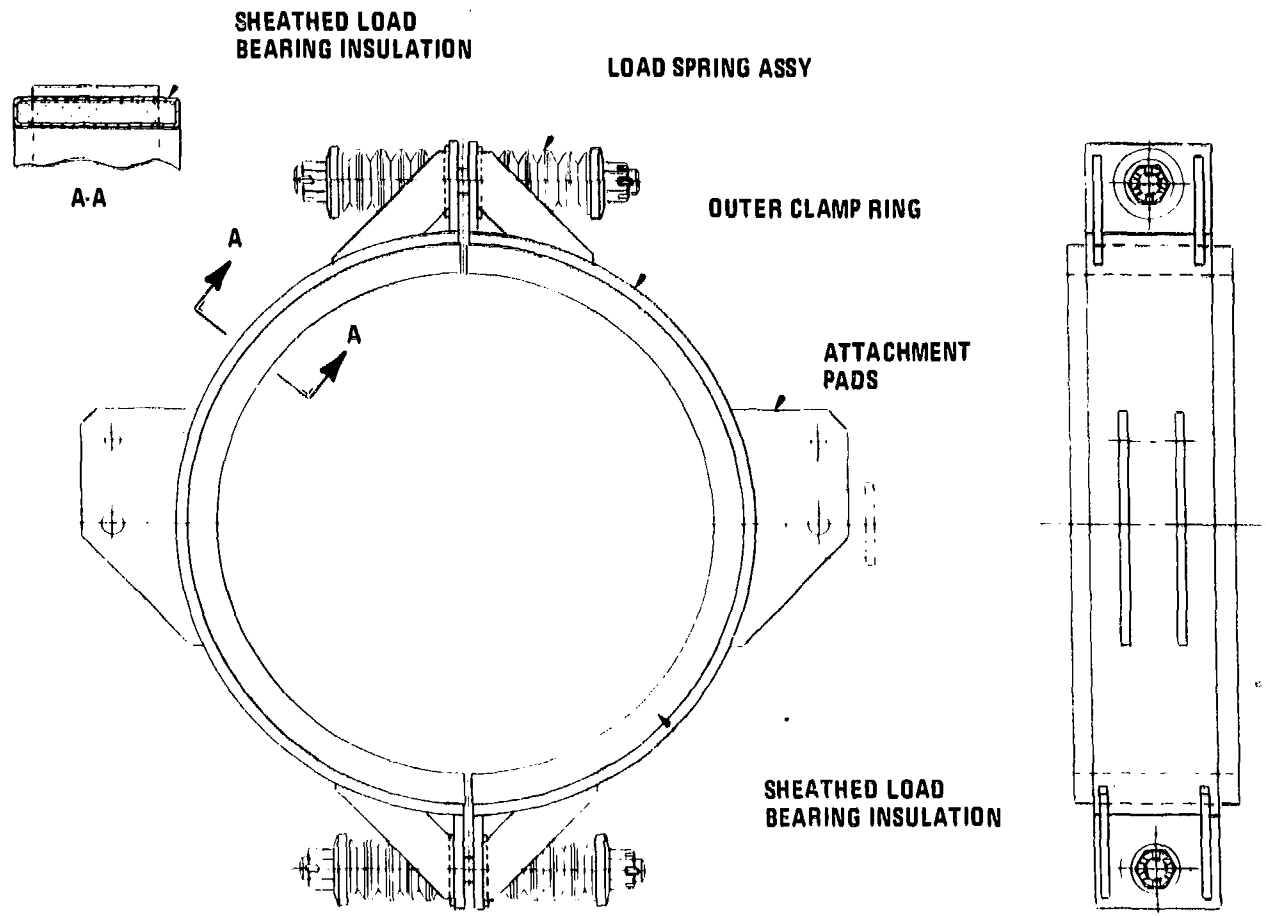

FIGURE 5: Horizontal Pipe Clamp Assembly

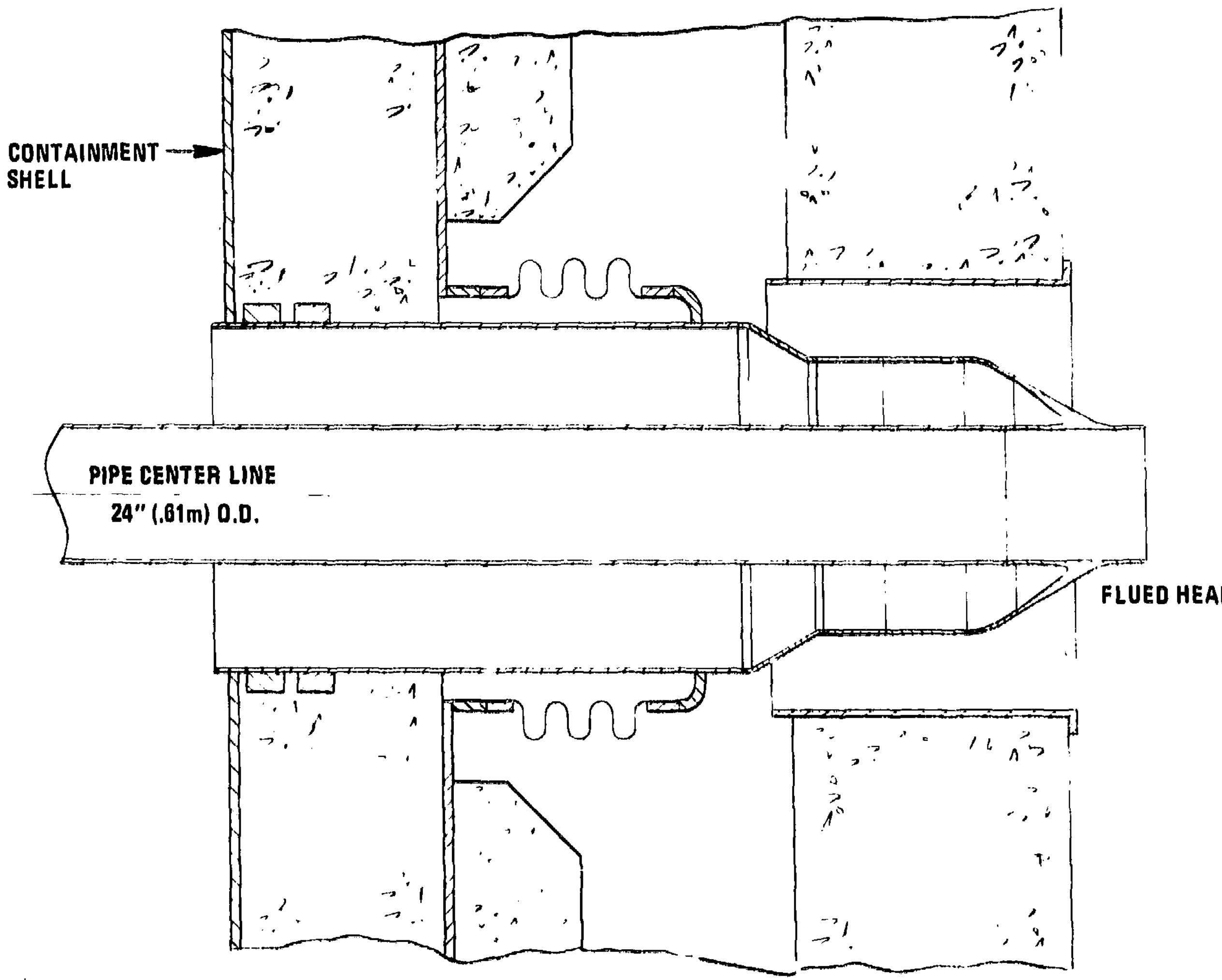

FIGURE 6: IHTS Piping Attachment at the Reactor Containment Building Penetration

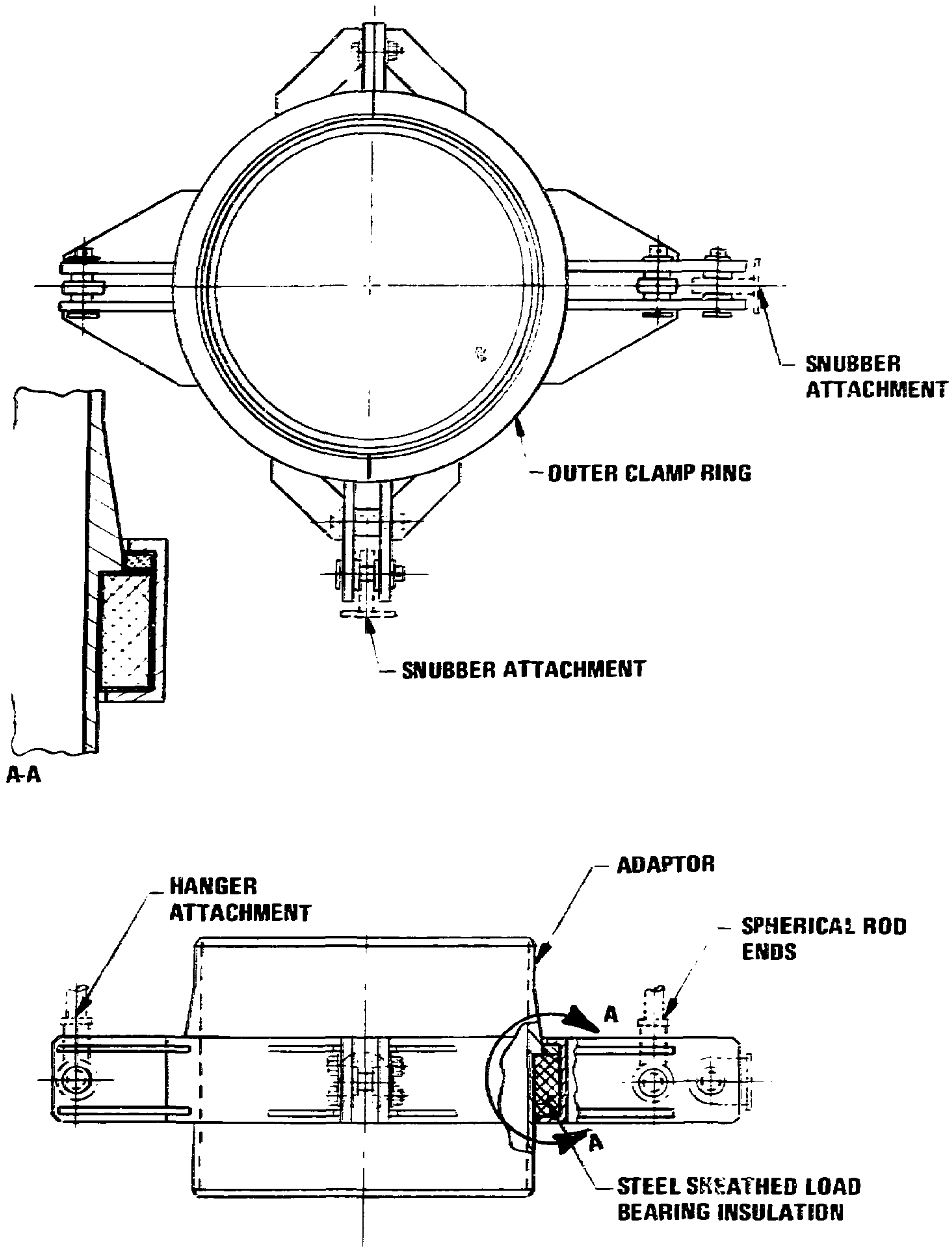

FIGURE 7: Vertical Pipe Clamp Assembly