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MARS VESSEL SAFETY ANALYSIS
For
Lawrence Livermore Laboratory
Livermore, California
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MARS Vessel Safety Analysis

LATA Report No. 115

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1.0 INTRODUCTION

A previous study¹ was performed to assess the hazards associated with an accidental leakage of cooling water into the crucible of molten ^{238}U for the MARS laser isotope separation experiment. That study evaluated the mechanisms and potential for a vapor-phase explosion during the experiment. The study found that the probability of such an explosion is extremely low during an accidental cooling system failure. An approximate calculation using conservative assumptions showed that the pressure loadings on the vacuum vessel might be high enough to impact the vacuum vessel design in the event of a vapor-phase explosion.

The purpose of the present study is to define a more realistic design basis accident (DBA) for the final MARS configuration, to obtain a better pressure transient history through the use of more exact calculational methods, and to evaluate the effects of the pressure on internal components with regard to their fragment-producing potential. The overall objective is to establish a design philosophy concerning a realistic DBA and to formulate design criteria for the vacuum vessel and its internal components.

2.0 DESCRIPTION OF THE DBA

An extremely severe explosion accident was postulated for the previous study¹ as a conservative base. In this study, the conservative parameters used before have been evaluated in detail and replaced with more realistic parameters. The parameters used in this study are the maximum credible parameters and, as such, still maintain adequate conservatism for an accident case involving a highly improbable accident.

2.1 Limiting Parameters Determining the DBA

The previous analysis postulated that a cooling system failure leaked water for at least 9 sec before the explosion occurred. This resulted in the optimum mix of water for a vapor-phase with the molten uranium quantities available. In addition, it assumed perfect mixing with 100% heat transfer efficiency. Thus, it assumed that 4,200 g of H_2O was heated to 305°C and the pressure released instantaneously.

Most vapor-phase explosions occur within 1 to 2 sec of contact.² The wait time is usually on the order of milliseconds. The realistic time before explosion, if indeed one were to occur, appears to be a maximum of 1 sec. With a flow rate of 31 gal/min, this would result in an accumulation of 1,960 cm³ of water within 1 sec (see Appendix A). Thus, instead of the 4,200 g of water assumed to react before, the value is now 1,960 g. The thermal efficiencies found in the literature are generally a few percent to 10%.^{1,2,3} Some experiments using shock tube initiation have produced efficiencies as high as 40%. Therefore, a value of 50% would not be overly conservative. Whereas the initial evaluation assumed that the water was superheated to 305°C (spontaneous nucleation temperature) and released instantaneously, the present study assumes an equation of state for the superheated water and a finite time for release. The time for all of the water to transform to steam is assumed to be approximately 60 μ s, (see Section 3.5) which is almost an order of magnitude slower than a high explosive (HE) detonation rate. The rate equation used is shown in Subsection 3.2.2.

The above changes are the only changes to the problem parameters from the initial study. The calculational methods have also been changed and are discussed in Section 3.0.

2.2 Margin of Safety

Design criteria governing the structural aspects of a vacuum chamber for the MARS experiment must be selected to provide assurance that the system will perform in accordance with acceptable practice. Unlike more commonly designed items that have established criteria based on precedence, there are no firmly established criteria governing all aspects of the MARS design, and it is therefore necessary to develop an integrated criteria package. The approach taken is to examine those criteria applicable to closely related activities and to extrapolate these to satisfy the intent of the requirements when applied to the MARS vessel, thus achieving an acceptable performance and equivalent risk of operation.

Facilities are assumed to be related to the MARS application if they have components and activities common to the following areas.

2.2.1 Type of Facility

Because the MARS facility will treat materials that may present some degree of radiological and industrial hazard, criteria applicable to both of these types of hazards are considered. For radiological comparisons, some precedent exists for establishing criteria for handling highly toxic and radiologically active substances such as plutonium and relatively more benign substances such as enriched uranium. Although plutonium handling criteria are considerably more stringent than those for natural or depleted uranium, the plutonium handling criteria will be used to serve as an upper limit for safety considerations.

Industrial hazards are considered to range from those events routinely treated in normal design codes to the more restrictive cases of

facilities expected to handle and process large quantities of HE. The explosive accident hazard for the MARS facility lies somewhere within this hazard range, and studies of these extremes will provide limits within which an acceptable risk may be established.

2.2.2 Service Conditions

Two service conditions are normally defined by the Department Of Energy (DOE) and Nuclear Regulatory Commission (NRC) criteria: 1) normal operation and 2) accident conditions. Other criteria, such as those encountered for private industry, usually do not separately specify such conditions but provide for some factor of safety, in that the assumed operating loads effectively include an accident contingency.

Criteria for accident conditions, including extreme environmental effects, are vastly different than those for normal operations. The definitions of load severity and the safety factors permitted in the design of elements are affected by the hazard potential of the process materials, which is considered to be relatively low in this case.

2.2.3 Regulatory Jurisdiction

If no established precedent exists, an understanding must be established with the proper regulating agency. In this case, the regulating agencies will be the Lawrence Livermore Laboratory (LLL) safety group and DOE. The requirements of these agencies can be met most easily if either DOE- or NRC-developed design criteria are used. The criteria established by NRC may be considered applicable to DOE projects by virtue of ERDAM 0521 and its acceptance by DOE IMD 5001.

When criteria are established by reference, inference, or extrapolation of requirements for related activities, some degree of acceptance uncertainty is inevitable. This may be minimized through communication with the persons or agencies exercising the authority of final judgment. In the case of LLL, close coordination with the facility safety committee may prove beneficial in reducing points of potential conflict.

Table 2-1 presents the salient points related to design criteria for activities with elements related to those of the MARS project. It covers a wide variety of facility types and the codes and standards associated with them. They are presented here to indicate a range of activities with which the MARS project can be compared.

From inspection of Table 2-1, it is concluded that the MARS facility presents a smaller hazard potential than does a plutonium facility or HE facility. The most similar hazard potential from nonreactor nuclear facilities appears to be that of the unirradiated enriched uranium storage facility as discussed in ERDAM Appendix 6301. Radiological problems for MARS are expected to be of a smaller potential magnitude than for the enriched uranium facility, but potential industrial hazard (explosion) may be greater.

Unfortunately, the margins of safety required for protection of personnel are somewhat general for the enriched uranium facility. Thus, a strategy must be employed to develop a margin of safety through design criteria and operational procedures that will satisfy the LLL safety committee and LOE. An evaluation of the potential hazards and the safety systems and design criteria that will tend to nullify these hazards by accident prevention or mitigation must be presented in the safety analysis report (SAR). DOE will then review the safety of the facility and determine whether the level of safety of the MARS facility is equivalent to that of similar facilities. Specific recommendations regarding the approach to the development of the design criteria for the MARS vacuum vessel and associated systems are discussed in Sections 4.0 and 5.0 of this report.

TABLE 2-1

A SURVEY OF DESIGN REQUIREMENTS FOR PROJECTS WITH COMPONENTS AND SAFETY IMPLICATIONS RELATED TO THOSE OF THE MARS PROJECT

<u>Code/Standard</u>	<u>Area of Applicability</u>	<u>Condition</u>	<u>Design Requirements and/or Guidance</u>
ERDAH 0531 Safety of Non- reactor Nuclear Facilities	Nonreactor Nuclear Facilities	Potential Significant Safety Hazards (assuming a release of a reasonable fraction of the nuclear material present) That Could Result in Any of the Following: <ol style="list-style-type: none"> 1. Radiation exposure in excess of established standards for offsite locations; 2. A significant hazard onsite due to exposure to radiation; 3. Significant property damage or loss onsite and/or offsite. 	<p>Conduct activities to assure:</p> <ol style="list-style-type: none"> 1. Identifiable risks no greater than those for comparable licensed nuclear facilities; 2. No undue risks to the health and safety of the public and employees. (Undue risk is defined as a level of identifiable risk that is unacceptable to ERDA/DOE.); 3. Protection of property and the environment from identifiable undue risks. <p>Prepare Operations Safety Requirements (OSRs) commensurate with the potential risks involved.</p> <p>Prepare a Safety Analysis Report (SAR) and include:</p> <ol style="list-style-type: none"> 1. Safety-related design criteria; 2. Evaluation of the risk associated with accidents from natural phenomena; 3. An evaluation of the engineered safety features to assure continued safe operation or safe shutdown under accident conditions; <p>Prepare Safety Assessment Document (SAD) and include assessment of the potential environmental, safety, and health (ES&H) risks or consequences if credible failures in safety systems and postulated operational errors occur. Include probable response to mitigate such accidents and their potential effects such that the probability of undue ES&H risks is precluded.</p>

TABLE 2-1
(continued)

<u>Code/Standard</u>	<u>Area of Applicability</u>	<u>Condition</u>	<u>Design Requirements and/or Guidance</u>
ERDAH Appendix 6301 Facilities General Design Criteria	Basic Design	General Guidelines	<p>Performance objectives to be achieved for protection against fire, explosion, and other hazards include:</p> <ol style="list-style-type: none"> 1. Protection of the public against injury, and protection of private property against damage; 2. Protection of employees from accidental injury and exposure to toxic materials and radiation in excess of the standards; 3. Protection of continuity of operations by minimizing accidents. <p>The significant hazards shall be carefully evaluated and protection provided in the design of the facility.</p>
		Structural Guidelines	<p>The basis of design and allowable unit stresses for var structural steel shall be in accordance with:</p> <p>"Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings," AISC.</p> <p>The loadings used in the structural design shall comply with:</p> <p>"American Standard Building Code Requirements for Minimum Design Loads in Buildings and Other Structures," ANSI A58.1</p>

TABLE 2-1
(continued)

Code/Standard	Area of Applicability	Condition	Design Requirements and/or Guidance
EMUAM Appendix 63D) (Continued)	Basic Design (Continued)	Earthquake	<p>Earthquake loads shall be in accordance with the applicable section of the International Conference of Building Officials' Uniform Building Code. Historical data shall be examined to determine the probable earthquake risk. Earthquake loading shall be applied concurrently with normal design loads, but not concurrently with wind loads. Good engineering judgement shall be used in designing structural systems to ensure that failures will not occur in critical members and joints.</p>
		Tornado	<p>Tornado design characteristics shall be determined from a review of historical damage records pertinent to the locality and the recommendation of NOAA and other qualified experts. Rotational and translational velocities, pressure drop, and induced missiles shall be fully considered in determining tornado loads. Tornado loadings shall be applied concurrently with normal design loads but not concurrently with earthquake loads.</p>
Unirradiated Enriched Uranium Storage Facilities		Design Basis Accidents	<p>The SAR shall define and document</p> <ol style="list-style-type: none"> 1. Design basis accidents and natural forces pertinent to the site and their credible combinations; 2. Possible hazards from operating and accident conditions; 3. The design basis accident resulting from the maximum accidental release from the storage facility of enriched uranium and fission products.

TABLE 2-1
(continued)

<u>Code/Standard</u>	<u>Area of Applicability</u>	<u>Condition</u>	<u>Design Requirements and/or Guidance</u>
ERDAM Appendix 6301 (Continued)	Unirradiated En- riched Uranium Storage Facilities (Continued)	Design Basis Accidents (Continued)	<p>The SAR shall assess natural forces pertaining to the site to define maximum credible natural events and consequent bases for design. To select design bases, existing historical data shall be examined in combination with safety factors consistent with the degree of potential hazard and with any uncertainties in defining design basis events such as natural phenomena, accident sequences, and the dispersal characteristics of any released material.</p> <p>In addition to normal dead and live loads, natural forces identified in the SAR such as floods, earthquakes, winds, and tornadoes shall be assessed in defining the design forces to be used in design.</p>
	Plutonium Facilities	Design Basis Accidents	<p>Critical items shall be designed to provide confinement of radioactive materials under normal operations and DBA conditions. In no case shall the applicable exposure regulations be exceeded either with respect to the operating personnel or to the public at the boundary. Consideration shall be given to the probability and effects of DBAs. Protection of employers within the facility shall be a consideration in all aspects of design.</p> <p>Structural design, including loading combinations and construction of critical safety and fire protection items, shall, as a minimum, be in accordance with pertinent nationally recognized codes and standards as referenced in ERDAM Appendix 6301, and the design criteria contained herein.</p>

TABLE 2-1
(continued)

<u>Code/Standard</u>	<u>Area of Applicability</u>	<u>Condition</u>	<u>Design Requirements and/or Guidance</u>
ERDAM Appendix S301 (Continued)	Plutonium Facilities (Continued)	Earthquake	<p>Procedures similar to those stated in "Seismic and Geologic Siting Criteria for Nuclear Power Plants," Appendix A to 10 CFR 100 shall be used for determining the quantitative design basis for vibrating ground motion at the site due to a DBE or OBE.</p> <p>The design basis earthquake (DBE) is defined as that earthquake which is the most severe DBA of this type. The operating basis earthquake (OBE) is equivalent to at least one-half the DBE in terms of ground acceleration.</p> <p>Critical items shall be designed to withstand the DBE and should be capable of continued operation after the occurrence of an OBE.</p> <p>The DBE or OBE shall be assumed capable of occurring at any time.</p> <p>For critical items, load combinations including normal design loads and the OBE loads shall be within normal working stress or deflection limits. Normal working stresses shall be those set forth in the codes referenced herein, including the appropriate stress increases or load factors for loading combinations with the appropriate earthquake.</p> <p>For materials other than concrete, load combinations, including normal operating loads and the DBE loads shall be within 95% of nominal yield stress or 1.5 times the normal allowable working stress, whichever is least.</p> <p>Critical items shall be designed to withstand load combinations including normal operating loads, DBE loads, and applicable DBA loads without loss of function. If operability of other than critical items is not required under a DBE or OBE, the BRC should be used for seismic design resistance.</p>

TABLE 2-1
(continued)

<u>Code/Standard</u>	<u>Area of Applicability</u>	<u>Condition</u>	<u>Design Requirements and/or Guidance</u>
ERDAM Appendix 6301 (Continued)	Plutonium Facilities (Continued)	Tornado	<p>The design basis tornado is the most severe of this type and with characteristics shown in exhibit 2 of ERDAM Appendix 6301, Part II, Section B. These characteristics are identical to those presented in Reg. Guide 1.76. The tornado shall be assumed capable of occurring at any time.</p> <p>Critical items shall be designed for the loads induced by tornadic forces, including missiles, in combination with applicable functional design loads.</p> <p>Steel members shall be designed with appropriate methods and 90% of yield values.</p>
		Other Natural Phenomena	Design loads and considerations shall provide a conservative margin of safety greater than the maximum historical levels recorded for the site.
		Explosion	The design basis explosion is defined as the most severe explosion applicable to the area under consideration. Critical items shall be designed to withstand the design basis explosion.
	High Explosives Facilities	Design Basis Accidents	The DBAs shall be postulated and the design of high explosives (HE) buildings shall assure that structures will meet the conditions imposed by the consequences of the postulated accidents.

TABLE 2-1
(continued)

<u>Code/Standard</u>	<u>Area of Applicability</u>	<u>Condition</u>	<u>Design Requirements and/or Guidance</u>
ERDAM Appendix 6301 (Continued)	High Explosives Facilities (Continued)	Design Basis Accidents (Continued)	<p>The objective is to achieve a level of safety greater than that provided by the provisions of AMCR 385-100. The levels of protection required may be accomplished by the provisions of AMCR 385-100.</p> <p>The levels of protection required for each hazard class are as follows:</p> <ol style="list-style-type: none"> 1. Class III (low accident potential) - bays shall provide protection from explosion propagation from bay to bay and between buildings; 2. Class II (moderate accident potential) - bays shall comply with Class III requirements and prevent personnel exposure to <ol style="list-style-type: none"> a. Overpressures greater than 15 psi Maximal Effective Pressure; b. Structural collapse of the building in the event of an explosion in the HE bay. 3. Class I (high accident potential) - bays shall comply with Class II requirements and prevent personnel exposure to <ol style="list-style-type: none"> a. Overpressure greater than 5 psi Maximum Effective Pressure; b. Structural collapse of the building; c. Missiles.

TABLE 2-1
(continued)

<u>Code/Standard</u>	<u>Area of Applicability</u>	<u>Condition</u>	<u>Design Requirements and/or Guidance</u>
ERDAH Appendix 6301 (Continued)	High Explosives Facilities (Continued)	Earthquake	Design parameters shall be developed by an analysis of the site conditions and the probable maximum seismic parameters. The seismic loading shall not be less than that specified in the UBC. The DBE shall be assumed capable of occurring at any time.
		Tornado	In designing bays for joint HE-plutonium activities, design basis tornado characteristics shall be equivalent to those for Plutonium Facilities.
10 CFR 50 Licensing of Production and Utilization Facilities	Production and Utilization Facilities	General Guidelines	<p>The definition of design bases includes specific values or ranges of values for controlling parameters as reference bounds for design. These values may be restraints determined from accepted practices or requirements derived from analyses of the effects of a postulated accident.</p> <p>A PSAR shall be prepared and shall contain the preliminary design of the facility including the design bases and information sufficient to provide reasonable assurance that the final design will conform to the design bases with adequate margin for safety.</p> <p>Structures shall be designed to quality standards commensurate with the importance of the safety function to be performed.</p>
		Earthquake	Design parameters should be developed with consideration of factors in 10 CFR 100.

TABLE 2-1
(continued)

Code/Standard	Area of Applicability	Condition	Design Requirements and/or Guidance
10 CFR 50 Appendix A General Design Criteria for Nuclear Power Plants	Nuclear Power Plants	Natural Phenomena	The design bases for structures important to safety shall reflect appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and time period in which data have been accumulated. Design bases shall also reflect appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena.
10 CFR 50 Appendix G Fracture Tough- ness Requirements	Nuclear Power Plants	Hydrostatic Tests and Normal Operation, Including Anticipated Operational Occurrences	Calculated stress intensity factors for vessels shall be lower than the reference stress intensity factors by the margins specified in the ASME Boiler and Pressure Vessel Code, Section III, Appendix G, "Protection Against Non-Ductile Failure." The calculation procedures shall comply with those specified in the ASME Code, Appendix G.
10 CFR 100 Reactor Site Criteria	Nuclear Power Plants	General Guidelines	To ensure a low risk of public exposure, factors to be considered when evaluating sites include the engineered safety features for safeguards against hazardous consequences of an accident, should one occur. Also to be considered are features having a significant bearing on the probability or consequences of accidental release of radioactive material.
		Earthquake	The required investigations are presented in 10 CFR 100 Appendix A, "Seismic and Geologic Siting Criteria for Nuclear Power Plants."

TABLE 2-1
(continued)

<u>Code/Standard</u>	<u>Area of Applicability</u>	<u>Condition</u>	<u>Design Requirements and/or Guidance</u>
10 CFR 100 Appendix A Seismic and Geologic Siting Criteria for Nuclear Power Plants	Nuclear Power Plants	Earthquake	<p>The most severe earthquakes associated with tectonic structures or tectonic provinces in the region surrounding the site should be identified, considering those historically reported earthquakes that can be associated with these structures or provinces and other relevant factors. The most severe earthquakes associated with faults in the region surrounding the site should be determined. The vibratory ground motion at the site should then be determined by assuming that the epicenters or locations of highest intensity of the earthquakes are situated at the point on the tectonic structures or provinces nearest the site.</p> <p>The earthquake that could cause the maximum vibratory ground motion at the site should be designated the Safe Shutdown Earthquake (SSE). In addition to seismic loads, including aftershocks, applicable concurrent functional and accident-induced loads shall be taken into account in the design of safety-related structures. It is permissible to design for strain limits in excess of yield strain in some of the safety-related structures during the SSE and under the postulated concurrent conditions, provided that the necessary safety functions are maintained.</p>
U.S. NRC Reg. Guide 1.26 Quality Group Classifications and Standards for Water-, Steam-, and Radioactive Waste-Containing Components of Nuclear Power Plants	Nuclear Power Plants	General Guidelines	<p>Group B quality standards should be applied to water- and steam-containing pressure vessels (et al.) that are part of the reactor coolant pressure boundary unless otherwise exempted.</p> <p>Group C quality standards should be applied to water-, steam-, and radioactive waste-containing pressure vessels (et al.) not part of the reactor coolant pressure boundary nor included in Quality Group B but part of the systems important to safety during emergency or accident conditions unless otherwise exempted.</p>

TABLE 2-1
(continued)

<u>Code/Standard</u>	<u>Area of Applicability</u>	<u>Condition</u>	<u>Design Requirements and/or Guidance</u>											
U.S. NRC Reg. Guide 1.26 Quality Group Classifications and Standards for Water-, Steam-, and Radioactive Waste-Containing Components of Nuclear Power Plants (Continued)	Nuclear Power Plants (Continued)	General Guidelines (Continued)	<p>Group D quality standards should be applied to water- and steam-containing pressure vessels (et al.) not part of the reactor coolant pressure boundary nor included in Quality Groups B or C but part of systems or portions of systems that contain or may contain radioactive material.</p> <p>A summary of requirements follows:</p> <table> <tr> <th rowspan="2"><u>Components</u></th><th colspan="3"><u>Quality Standards</u></th></tr> <tr> <th><u>Quality B</u></th><th><u>Quality C</u></th><th><u>Quality D</u></th></tr> <tr> <td>Pressure Vessels</td><td>ASME Boiler and Pressure Vessel Code, Section III, "Nuclear Power Plant Components," Class 2.</td><td>ASME Boiler and Pressure Vessel Code, Section III, "Nuclear Power Plant Components," Class 3.</td><td>ASME Boiler and Pressure Vessel Code, Section VIII, Division 1.</td></tr> </table>	<u>Components</u>	<u>Quality Standards</u>			<u>Quality B</u>	<u>Quality C</u>	<u>Quality D</u>	Pressure Vessels	ASME Boiler and Pressure Vessel Code, Section III, "Nuclear Power Plant Components," Class 2.	ASME Boiler and Pressure Vessel Code, Section III, "Nuclear Power Plant Components," Class 3.	ASME Boiler and Pressure Vessel Code, Section VIII, Division 1.
<u>Components</u>	<u>Quality Standards</u>													
	<u>Quality B</u>	<u>Quality C</u>	<u>Quality D</u>											
Pressure Vessels	ASME Boiler and Pressure Vessel Code, Section III, "Nuclear Power Plant Components," Class 2.	ASME Boiler and Pressure Vessel Code, Section III, "Nuclear Power Plant Components," Class 3.	ASME Boiler and Pressure Vessel Code, Section VIII, Division 1.											
U.S. NRC Reg. Guide 1.48 Design Limits and Loading Combinations for Seismic Category 1 Fluid System Components	Nuclear Power Plants	Earthquake	<p>This guide delineates acceptable design limits and appropriate combinations of loadings associated with normal operation, postulated accidents, and seismic events for design of Seismic Category 1 fluid system components.</p>											

TABLE 2-1
(continued)

<u>Code/Standard</u>	<u>Area of Applicability</u>	<u>Condition</u>	<u>Design Requirements and/or Guidance</u>
U.S. NRC Reg. Guide 1.48 Design Limits and Loading Combinations for Seismic Category 1 Fluid System Components (Continued)	Nuclear Power Plants (Continued)	Earthquake (Continued)	<p>Definitions:</p> <ol style="list-style-type: none"> 1. Allowable stress value (S) - as specified in Appendix I of Section III of the ASME Boiler and Pressure Vessel Code. 2. Emergency plant condition - those operating conditions that have a low probability of occurrence. 3. Faulted plant condition - those operating conditions associated with extremely-low probability postulated events. 4. Upset plant condition - those deviations from the normal plant condition that have a high probability of occurrence.

In the application of design limits, the design conditions should reflect the most adverse combination of loadings to which the components may be subjected. These limiting conditions correspond to low-probability postulated accidents or events.

Design limits for vessels are as follows:

1. ASME Code Class 1 Vessels.
 - a. Design limits specified as Level B Service Limits (NB-3223) in the ASME Code, Section III should not be exceeded when the component is subjected to concurrent loadings associated with either the normal plant condition or the upset plant condition and the vibratory ground motion of 50% of the SSE.
 - b. Design limits specified as Level C Service Limits (NB-3224) in the ASME Code should not be exceeded when the component is subjected to loadings associated with the emergency plant condition.

TABLE 2-1
(continued)

Code/Standard	Area of Applicability	Condition	Design Requirements and/or Guidance
U.S. NRC Reg. Guide 1.4B Design Limits and Loading Combinations for Seismic Category I Fluid System Components (Continued)	Nuclear Power Plants (Continued)	Earthquake (Continued)	<p>c. Design limits specified as Level D Service Limits (NB-3225) in the ASME Code should not be exceeded when the component is subjected to concurrent loadings associated with the normal plant condition, the vibratory motion of the SSE, and the dynamic system loadings associated with the faulted plant condition.</p> <p>2. ASME Code Class 2 and 3 Vessels (designed to Division 1 of Section VIII).</p> <p>a. The allowable stress value S should not be exceeded by more than 10% when the component is subjected to either</p> <ol style="list-style-type: none"> (1) concurrent loadings associated with either the normal plant condition and the vibratory motion of 50% of the SSE, or (2) loadings associated with the emergency plant condition. <p>b. S should not be exceeded by more than 50% when the component is subjected to concurrent loadings associated with the normal plant condition, the vibratory motion of the SSE, and the dynamic system loadings associated with the faulted plant condition.</p> <p>3. ASME Code Class 2 Vessels (designed to Division 2 of Section VIII).</p> <p>Section III of the ASME Code allows Code Class 2 vessels to be designed to Division 2, Section VIII rules. Division 2 provides rules that are equivalent to those of Section III for Code Class 1 vessels. Also, the quality level for Division 2 vessels is comparable to that for Code Class 1 vessels of Section III. Therefore, the design limits should be the same as for Code Class 1 vessels as presented above.</p>

TABLE 2-1
(continued)

2-18

Code/Standard	Area of Applicability	Condition	Design Requirements and/or Guidance																																				
U.S. NRC Reg. Guide 1.76 Design Basis Tornado for Nuclear Power Plants	Nuclear Power Plants	Tornado	<p>Nuclear power plants must be designed so that the plants remain in a safe condition in the event of the most severe tornado that can reasonably be predicted to occur at a site. Nuclear power plants should be designed to withstand the Design Basis Tornado (DBT) defined below:</p> <table><tr><th rowspan="2">Region</th><th>Maximum Wind Speed (mph)</th><th>Rotational Speed (mph)</th><th colspan="2">Translational Speed (mph)</th><th rowspan="2">Radius of Maximum Rotational Speed (ft)</th><th rowspan="2">Pressure Drop (psi)</th><th rowspan="2">Rate of Pressure Drop (psi/sec)</th></tr><tr><th></th><th></th><th>Maximum</th><th>Minimum</th></tr><tr><td>I</td><td>360</td><td>290</td><td>70</td><td>5</td><td>150</td><td>3.0</td><td>2.0</td></tr><tr><td>II</td><td>300</td><td>240</td><td>60</td><td>5</td><td>150</td><td>2.25</td><td>1.2</td></tr><tr><td>III</td><td>240</td><td>190</td><td>50</td><td>5</td><td>150</td><td>1.5</td><td>0.6</td></tr></table>	Region	Maximum Wind Speed (mph)	Rotational Speed (mph)	Translational Speed (mph)		Radius of Maximum Rotational Speed (ft)	Pressure Drop (psi)	Rate of Pressure Drop (psi/sec)			Maximum	Minimum	I	360	290	70	5	150	3.0	2.0	II	300	240	60	5	150	2.25	1.2	III	240	190	50	5	150	1.5	0.6
Region	Maximum Wind Speed (mph)	Rotational Speed (mph)	Translational Speed (mph)		Radius of Maximum Rotational Speed (ft)	Pressure Drop (psi)	Rate of Pressure Drop (psi/sec)																																
			Maximum	Minimum																																			
I	360	290	70	5	150	3.0	2.0																																
II	300	240	60	5	150	2.25	1.2																																
III	240	190	50	5	150	1.5	0.6																																
			<p>These characteristics are identical to those specified in EROAM Appendix 6301, Part II, B for Plutonium Facilities.</p>																																				
ASME Boiler and Pressure Vessel Code, Section III	Pressure Vessels	General Guidelines	<p>The design shall be such that stress intensities will not exceed the limits specified for the particular material in use. For Type 304 stainless steel plate, the design stress intensity values, S_m, as a function of temperature, are as follows:</p> <table><tr><th rowspan="2">Minimum Yield Strength (ksi)</th><th rowspan="2">Minimum Ultimate Tensile Strength (ksi)</th><th colspan="10">Design Stress Intensity (S_m), ksi, for Metal Temperatures, °F, not to Exceed</th></tr><tr><th>100</th><th>200</th><th>300</th><th>400</th><th>500</th><th>600</th><th>650</th><th>700</th><th>750</th><th>800</th></tr><tr><td>30.0</td><td>75.0</td><td>20.0</td><td>20.0</td><td>20.0</td><td>18.7</td><td>17.5</td><td>16.4</td><td>16.2</td><td>16.0</td><td>15.6</td><td>15.2</td></tr></table>	Minimum Yield Strength (ksi)	Minimum Ultimate Tensile Strength (ksi)	Design Stress Intensity (S_m), ksi, for Metal Temperatures, °F, not to Exceed										100	200	300	400	500	600	650	700	750	800	30.0	75.0	20.0	20.0	20.0	18.7	17.5	16.4	16.2	16.0	15.6	15.2		
Minimum Yield Strength (ksi)	Minimum Ultimate Tensile Strength (ksi)	Design Stress Intensity (S_m), ksi, for Metal Temperatures, °F, not to Exceed																																					
		100	200	300	400	500	600	650	700	750	800																												
30.0	75.0	20.0	20.0	20.0	18.7	17.5	16.4	16.2	16.0	15.6	15.2																												

TABLE 2-1
(continued)

<u>Code/Standard</u>	<u>Area of Applicability</u>	<u>Condition</u>	<u>Design Requirements and/or Guidance</u>								
ASME Boiler and Pressure Vessel Code, Section III (Continued)	Pressure Vessels (Continued)	General Guidelines (Continued)	The design limits for the various stress components are functions of the values of S_m . A summary of primary stress design limitations follows:								
			<table><tr><th><u>Stress Category</u></th><th><u>Stress Intensity Limit</u></th></tr><tr><td>General Membrane (P_m)</td><td>S_m</td></tr><tr><td>Local Membrane (P_1)</td><td>$1.5 S_m$</td></tr><tr><td>Local Membrane Plus Bending ($P_1 + P_b$)</td><td>$1.5 S_m$</td></tr></table>	<u>Stress Category</u>	<u>Stress Intensity Limit</u>	General Membrane (P_m)	S_m	Local Membrane (P_1)	$1.5 S_m$	Local Membrane Plus Bending ($P_1 + P_b$)	$1.5 S_m$
<u>Stress Category</u>	<u>Stress Intensity Limit</u>										
General Membrane (P_m)	S_m										
Local Membrane (P_1)	$1.5 S_m$										
Local Membrane Plus Bending ($P_1 + P_b$)	$1.5 S_m$										

Service limits for Levels A, B, or C depend upon primary and secondary load combinations and have values that are multiples (≥ 1.0) of S_m . Level D limits are determined by other methods.

Except in local regions, the thickness of cylindrical shells for a vessel shall never be less than that obtained by

$$t = \frac{PR}{S_m - 0.5P} \quad \text{or} \quad t = \frac{PR_o}{S_m + 0.5P},$$

where

t = thickness of shell or head, in.,

P = design pressure, psi.,

R = inside radius of shell or head, in.,

R_o = outside radius of shell or head, in., and

S_m = design stress intensity values.

TABLE 2-1
(continued)

<u>Code/Standard</u>	<u>Area of Applicability</u>	<u>Condition</u>	<u>Design Requirements and/or Guidance</u>													
ASME Boiler and Pressure Vessel Code, Section VIII, Division 1	Pressure Vessels	General Guidelines	The maximum allowable tensile stress, S, permitted for 304 stainless steel plate, as a function of temperature, is as follows													
			Specified Minimum Yield (ksi)		Specified Minimum Tensile (ksi)		Maximum Allowable Stress (S), ksi, Metal Temperatures, °F, not to Exceed									
			<u>100</u>	<u>200</u>	<u>300</u>	<u>400</u>	<u>500</u>	<u>600</u>	<u>650</u>	<u>700</u>	<u>750</u>	<u>800</u>				
			30.0	75.0	18.8	15.7	14.1	12.9	12.1	11.4	11.2	11.1	10.8	10.6		

The minimum thickness or maximum allowable working pressure for cylindrical shells under internal pressure shall be the greater thickness or lesser pressure as given by (1) or (2):

Circumferential Stress

$$t = \frac{PR}{SE - 0.6P} \quad \text{or} \quad P = \frac{SEt}{R + 0.6t} \quad (1)$$

when the thickness does not exceed one-half of the inside radius, or P does not exceed $0.385 SE$, or

Longitudinal Stress

$$t = \frac{PR}{2SE + 0.4P} \quad \text{or} \quad P = \frac{2SEt}{R - 0.4t} \quad (2)$$

when the thickness does not exceed one-half of the inside radius, or P does not exceed $1.25 SE$,

where

- t = minimum required thickness, in.,
- R = inside radius,
- S = maximum allowable stress value, psi., and
- E = joint efficiency.

Area of Code/Standard	Applicability	Design Requirements and/or Guidance
ASME Boiler and Pressure Vessel Code, Section VIII, Division 2	Pressure Vessels	General Guidelines
		These rules are more restrictive than Division 1 in the choice of materials but permit higher design stress intensity values in the range of temperatures over which the design stress intensity value is controlled by the ultimate strength or the yield strength. In addition, more precise design procedures are required and some common design details are prohibited.

3.0 DBA PRESSURE TRANSIENT LOADS

An estimate of the pressure transient loads is required for the wall of the vacuum vessel as well as for internal components. The method of calculation of these pressure histories as well as all assumptions are discussed in this section.

3.1 Hydrodynamics Computer Code

A one-dimensional reactive flow computer code, PAD⁴, was used to simulate the transformation of superheated liquid water to steam and to produce the subsequent pressure-time history in the vessel. This code is documented and has been used at the Los Alamos Scientific Laboratory to solve explosion problems.

The computer model represents an approximation to the actual problem: initially the explosion is with a one-point detonation, but the vessel geometry is cylindrical. The vessel dimensions are 5.5 ft diameter and 12 ft length. The initial pressure interactions with the wall should be adequate. However, subsequent reflections from walls and ringing may be unrealistic. In particular, because of the 1-D geometry, the pressure will remain artificially high for periods of time that are too long. In the actual geometry, the pressure wave will not be reflected back perfectly from the source point but will interact with the copper crucible and other internal components. The effect of these assumptions is discussed further in Subsection 3.2.3.

Even with the restrictions placed on problem geometry by the computer program, the initial part of the pressure history is deemed adequate for the purpose of this safety analysis. The subsequent pressure decay can be approximated using experimental results and engineering judgment that should be adequate, because this portion of the pressure history is secondary in nature compared with the initial interaction. Even a two-dimensional code would have difficulty in producing results accurate to better than a factor of two. Given the

problem definition, input parameters and the cost increment, a 2-D or possibly 3-D hydrocode solution would not be justified for the present purpose.

3.2 Problem Formulation

The calculations involved in formulating the input for the problem are contained in Appendix A. These results are used in this section.

3.2.1 Geometry

A simple rendition of the actual geometry of the experiment is shown in Figure 3-1. Internal components, windows, and plenums are not shown. Figure 3-2 shows the calculational counterpart to the actual geometry. The copper crucible is treated as a rigid surface, followed by a spherical mass containing the reacting water. A rarified steam atmosphere is inserted between the reacting water and the vacuum vessel.

3.2.2 Equations of State

The PAD program requires the use of material equations-of-state in order to simulate the transformation kinetics. The liquid water is modeled by a simple Gruneisen equation. When this liquid has been completely converted to steam, an equation-of-state for steam alone is used. For steam, a polytropic gas equation-of-state has been used which is in excellent agreement with BKW calculations for steam in the pressure range of interest (45,000 psia or less).

During the reaction, the two equations-of-state must be mixed in order to calculate properties of the partially reacted state. This was accomplished using a mixing rule called BLEND.⁴ This is a simple pressure mix rule using a stiffness parameter and a heat of reaction.

OPERATING CONDITIONS

1. Chamber Pressure $\sim 10^{-6}$ Torr
2. Crucible Cooling ~ 150 gpm at 80 psi
3. Vapor Shield Cooling ~ 80 gpm at 80 psi
4. Electron Gun Cooling ~ 40 gpm at 80 psi

MARS Chamber Configuration

Figure 3-1

PAD Calculational Geometry

Figure 3-2

The entire equation-of-state structure is summarized by the following system of equations:

Liquid Equation-of-State (Gruneisen)

$$P_L = P_{\text{reference}} + \rho_{OL} \Gamma_L (e - e_{\text{reference}})$$

where

$$P_{\text{reference}} = 0 \text{ (initially),}$$

$$e_{\text{reference}} = 0 \text{ (initially),}$$

$$\rho_{OL} = \text{initial density of the liquid,}$$

$$\Gamma_L = \text{Gruneisen Ratio (0.109).}$$

(3-1)

Steam Equation-of-State (Polytropic Gas)

$$P_G = (\gamma - 1) \rho_G e$$

where

$$\gamma = \text{ratio of specific heats (1.32) and}$$

$$\rho_G = \text{gas density.}$$

(3-2)

Mixture Equation of State (BLEND)

$$P = K[(1 - \lambda)P_l(e + \lambda q) + \lambda P_g(e)]$$

where

$$K = 1 - 5\lambda(1-\lambda),$$

$$\lambda = \text{mass fraction of steam,}$$

$$S = \text{stiffness parameter (2/3), and}$$

$$q = \text{enthalpy of transformation (2.24 kJ/g).}$$

(3-3)

The final equation needed to completely specify the system is a reaction rate governing the evolution of the steam mass fraction λ . As stated before, the reaction is assumed to have a reaction rate in this study, whereas, in the preliminary study it was assumed to be instantaneous.

A simple reaction rate was chosen with a depletion rate depending linearly on the system density. It has the form

$$\dot{\lambda} = k\rho(1 - \lambda)^{\frac{1}{2}}.$$

A value of $k = 1$ results in a complete reaction in approximately 3 μ s; a value of $k = 0.1$ results in a complete reaction in about 60 μ s. For all of the numerical calculations, a value of $k = 0.1$ has been used. The reaction rate assumed for a vapor-phase explosion is about an order of magnitude less than rates for HE detonations.

3.2.3 Assumptions and Approximations

The calculation is carried out in spherical geometry. A rigid wall (copper crucible) is at zero radius, followed by 71.2 mm of water (1,514 g). At a radius of 853 mm, the containment wall is inserted with the intervening space assumed to be low density steam (2.5 psia). At zero-time the water has an initial pressure of 7,800 psi (0.054 GPa) and is allowed to begin expansion and reaction simultaneously. The uranium is assumed to have no involvement in the hydrodynamics but is treated simply as a source of energy for the water.

The dynamic behavior of the actual system is extremely difficult to predict. First, the kinetics of the water-steam transformation at varying degrees of superheat are not known with great certainty. Second, the details of the dynamics of the liquid-liquid contact have a profound effect on the resulting explosive potential of the system. Third, the degree of intimate mixing of the water with molten uranium is not well known. With these uncertainties and those of the input parameters, it is not reasonable to assume with 80% confidence that the case discussed in this report is the one that may occur in fact. However, the case presented here is representative, and it is unlikely that a real event could be greater than this theoretical case by more than a factor of two. What is presented here is a good estimate of the

evolution of a steam explosion in a one-dimensional calculational geometry as reminiscent of the actual geometry as possible. The results should then be adequate for design and safety purposes with the degree of accuracy in mind.

3.3 Results

The pressure-time history at the vacuum vessel wall is presented in Figure 3-3. The peak pressure predicted by the computer code is about 113 psi. The duration of the pressure pulse is only a few hundred microseconds (μs). Detailed plots of pressure, velocity, and density as a function of position are shown in Appendix B. It should be noted that, in these plots, the boundary between the source region and the steam atmosphere moves outward with time. The shock wave shows up clearly just outside that boundary in the pressure versus position plots.

The interaction of the pressure pulse with the vacuum vessel, internal components, and the plenum is discussed in Section 5.

Pressure - Time History At Vacuum Vessel Wall
Figure 3-3

4.0 FRAGMENT-PRODUCING POTENTIAL OF INTERNAL COMPONENTS

If a vapor explosion occurs in the MARS vessel, the possibility of producing fragments and missiles must be considered. Such fragments could potentially be produced as the explosive blast impacts the various internal components inside the vessel, and in turn these could possibly strike the vessel wall with sufficient force to damage or penetrate the wall. This section considers a preliminary assessment of this fragment hazard.

4.1 Approach

A parametric approach was taken to investigate the fragment hazard, because relatively little detail was available on the planned internal components, and if it was shown that the worst credible fragment does not penetrate the vessel, there is no point in further considering this hazard.

As the shock wave strikes the various internal objects, the pressure differential between the front and back faces will have its maximum value when the shock wave has not yet completely surrounded the structure. Such a pressure differential will produce a lateral (or translational) force tending to cause the structure to deflect and move bodily, usually in the same direction as the blast wave. This force is known as the "diffraction loading" because it operates while the shock wave is being diffracted around the structure. The extent and nature of the actual motion will depend upon the size, shape, and weight of the component and how firmly it is attached to the support structure. This phenomenon is illustrated in Figure 4-1 below.

In detail, the approach taken to estimate the fragment penetration hazard to the vessel walls is as follows:

- (1) Calculate the shock wave characteristics (pressure-time history) at various distances out from the vapor phase explosion source;

Illustration Of Diffraction Loading
On An Internal Component

Figure 4-1.

- (2) Integrate the pressure-time history to obtain the diffraction loading impulse;
- (3) Assume a range of fragment frontal areas (A) and fragment masses (M) to represent the various frangible internal components in the MARS vacuum vessel;
- (4) Calculate the transformation from impulse to kinetic energy as

$$\frac{I^2}{2M} = \frac{Mv_o^2}{2}$$

where

I = impulse of incident shock wave,

M = mass of fragment, and

v_o = resultant velocity of fragment. (4-1)

This equation is then solved for the resultant velocity (V) of the fragments:

- (5) Calculate the vacuum vessel wall perforation thickness, assuming that the fragments are steel. Other softer metals, such as copper, will have less penetration capability; so the assumption of steel fragments is conservative for some of the internal components. The perforation thickness (e) is calculated by the Stanford Equation.^{5,6} As explained in Reference 7, this recently developed equation is now accepted for use to predict fragment and missile perforation of nuclear power facilities.

4.2 Pressure-Time Histories

The vapor explosion, shock wave, pressure-time history was derived from the PAD hydrocode calculations described in Subsection 3.1 of this report. The pressure-position profiles at various times are shown in Figures 4-2 and 4-3 as calculated by the PAD code.

Fixed radial positions from the explosion source were chosen as 30%, 60%, and 90% of the distance to the vessel wall (838 mm). The pressure-time profile at these three radial positions was derived from the pressure-position profiles in Figures 4-2 and 4-3. This mapping into the time domain results in Figures 4-4, 4-5, and 4-6. The shape of the pressure histories is approximated from the interpolation of PAD results and is not exact; however, it makes little difference as far as fragment velocity is concerned. The critical parameter here is the impulse or integrated area under the pressure-time profile; this is fairly insensitive to irregularities in the profile.

The results are summarized in Table 4-1.

Time = 200 μ s

Time = 400 μ s

Time = 600 μ s

Time = 800 μ s

Vapor Phase Explosion Pressure Profiles -
Prior To Wall Contact

Figure 4-2

Los Alamos Technical Associates, Inc.

Time = 1000 μ s

Time = 1200 μ s

Time = 1400 μ s

Time = 1600 μ s

Vapor Phase Explosion Pressure Profiles -
Reflection From Walls

Figure 4-3

Pressure - Time Profile At 30% Radial Position

Figure 4-4

Pressure - Time Profile At 60% Radial Position

Figure 4-5

Pressure - Time Profile At 90% Radial Position

Figure 4-6

TABLE 4-1
PRESSURE IMPULSE PREDICTED AT STATIONS INSIDE VESSEL

<u>Position (% of wall radius)</u>	<u>Impulse (GPa - μs)</u>
30	11×10^{-4}
60	4×10^{-4}
90	4×10^{-4}

4.3 Parametric Results

A range of credible sized fragments were assumed for the parametric analysis. Frontal areas were assumed to vary from 0.01 m^2 to as much as 1.0 m^2 , and the masses were assumed to range from 0.01 to 1.0 kg. This restricted set of nine possible fragments was then analyzed for perforation capability. If these fragments do not approach a vessel wall perforation (1/2 in. thick steel), then it is not necessary to investigate other fragment sizes. More importantly, if these fragments do not present a threat to the vessel integrity, there is no need to perform the complex analysis of blast failure and fragment generation from the actual MARS system internal components.

As mentioned previously, the Stanford Equation^{5,6} was used to predict the perforation of the steel wall by steel fragments. This equation is:

$$\left(\frac{e}{d}\right)^2 + \frac{3F}{128} \left(\frac{e}{d}\right) = \frac{0.0452 D_v^2}{S_s}$$

where

e = perforation thickness, i.e., the maximum thickness of a target which a missile with a given impact velocity will completely penetrate, (in),

$$\begin{aligned}
 d &= \text{missile diameter or effective diameter for noncircular cross sections based upon equivalent area. (in.),} \\
 B &= \text{width of steel target plate between rigid supports, (in.),} \\
 D &= W/d^3, \text{ (lb/in.)}^3, \\
 W &= \text{weight of projectile, (lb),} \\
 v_o &= \text{impact velocity normal to plate, (fps),} \\
 S_s &= \text{ultimate tensile strength of steel plate, (psi), and} \\
 F &= \text{minimum of } \frac{B/D}{8 \cdot 100 (e/d)}. \quad (4-2)
 \end{aligned}$$

The following assumptions were used to apply this equation to the subject analysis:

- (1) fragments are solid cubic shapes with a frontal area A,
- (2) the ultimate tensile strength (S_s) of the wall is 80,000 psi, and
- (3) the factor F is minimized by 100 (e/d); this was confirmed by the subsequent calculations.

The final results of the perforation calculation are shown in Table 4-2 and plotted in Figures 4-7 and 4-8.

For a vacuum vessel wall made of 1/2-in.-thick steel (12.7 mm), the postulated set of fragments do not present a threat. The most serious fragment that originates from a point 30% of the radius from the explosion source would penetrate only 0.0816 mm into the wall. For the fragments originating farther out at 60% and 90% of the radius, the threat is even less because they would penetrate only 0.0297 mm into the wall. Therefore, it is concluded that explosive-driven fragments from the various internal components in the vacuum vessel do not present a threat to the vessel wall.

TABLE 4-2
ESTIMATED FRAGMENT PENETRATION

<u>Originating Location (°R)</u>	<u>Fragment</u>		<u>Perforations</u>
	<u>Frontal Area (m²)</u>	<u>Mass (kg)</u>	<u>e (mm)</u>
30.0	0.01	0.01	2.57×10^{-3}
	0.01	0.01	8.17×10^{-4}
	0.01	1.0	2.58×10^{-4}
	0.1	0.01	1.45×10^{-2}
	0.1	0.1	4.6×10^{-3}
	0.1	1.0	1.45×10^{-3}
	1.0	0.01	8.16×10^{-2}
	1.0	0.1	2.58×10^{-2}
	1.0	1.0	8.18×10^{-3}
60 & 90	0.01	0.01	9.37×10^{-4}
	0.01	0.1	2.97×10^{-4}
	0.01	1.0	9.39×10^{-5}
	0.1	0.01	5.28×10^{-3}
	0.1	0.1	1.67×10^{-3}
	0.1	1.0	5.28×10^{-4}
	1.0	0.01	2.97×10^{-2}
	1.0	0.1	9.4×10^{-3}
	1.0	1.0	2.97×10^{-3}

Figure 4-7 Fragment penetration. (Fragments originated at 30° radial position.)

Figure 4-8 Fragment penetration. (Fragments originated at 60% and 90% radial position.)

5.0 DESIGN CRITERIA

The philosophy of specifying design criteria is to assure that the system (MARS vacuum vessel in this case) will meet the requirements of a Safety Analysis Report (SAR). Structural components of the vacuum vessel, and its associated piping, should be designed to function in its normal service within the allowable stress limitation imposed by the ASME Section VIII code. However, accident conditions shall be evaluated on the basis of the requirements of ERDAM 6301 and 0531, which permit higher allowable stresses for severe and rare loading events. It is then assumed that safety of operating personnel and the general public can be assured if the vessel remains essentially intact and no missiles, fragments, or steam jets could strike operating personnel.

This assurance can be accomplished with a small residual margin of safety if stresses are permitted to approach the yield strength of the structural material. A precedent for allowing material stresses to approach the material yield strength exists for certain rare loading conditions in ERDAM 6301, Part II, Section B, "Plutonium Facilities Design Criteria." However, a failure of the MARS vessel should not be construed as being as serious as an analogous accident at a plutonium facility.

ERDAM 6301 recommends that the accident condition should allow material stresses to reach 95% of yield stress or 1.5 times the allowable working stress, whichever is less. However, selected parts or components should be permitted to yield if their post-yield behavior can readily be predicted. Large deformation should not be tolerated, and the predicted post-yield behavior should be such that no failure of any safety-related component or subsystem will occur.

5.1 Vacuum Vessel

The vacuum vessel (shown in Figure 3-1) may be subjected to the DBA vapor-phase explosion, as described previously in Sections 2.0 and

3.0. This unlikely event will cause a transient pressure loading for which the vessel walls must be designed. This section considers the stress analysis of vessel wall subjected to the pressure transient described in Section 3.0 and shown in Figure 3-2.

5.1.1 Stress Analysis

Using the pressure transient input, we can make a calculation of vessel wall response to describe stress, displacement, velocity, and acceleration histories. Then, assuming a pressure vessel of 33-in. radius with wall thickness of 0.5 in., an equivalent single degree-of-freedom system of the following characteristics results:

$$\begin{aligned} \text{mass} &= 3.667 \times 10^{-4}, \\ k(\text{spring const}) &= 13,774 \text{ \#/in.}, \\ \text{initial displacement (vacuum effects)} &\approx -0.000853 \text{ in.}, \text{ and} \\ \text{force} &= (\text{see Figure 3-2}). \end{aligned} \tag{5-1}$$

A step by step time history using a constant linear acceleration method reveals the following vessel response:

$$\begin{aligned} \text{maximum displacement of vessel wall} &= 7.34 \times 10^{-3} \text{ in.}, \\ \text{maximum vessel wall stress} &= 6,666 \text{ psi}, \\ \text{time of maximum response} &= 460 \times 10^{-6} \text{ sec, (measured from the time} \\ &\text{that the pressure pulse is applied to the vessel wall).} \end{aligned} \tag{5-2}$$

As a check on the above results, an ideal, 100% efficient, strain energy conversion is assumed. This makes use of an equivalent triangular pulse shape of equal impulse (H) of 0.025 psi's. Using data for a 66-in.-circular cross-section vessel with a 0.5-in. wall, we find that an equivalent single degree of freedom system has the following dynamic characteristics:

$$\begin{aligned} \omega &= \sqrt{k/m} = \sqrt{13774/3.667 \times 10^{-4}} = 6129 \text{ rad/sec,} \\ f &= 6129 \div (2\pi) = 975 \text{ rev/sec, and} \\ T &= 1/f = 1025 \times 10^{-6} \text{ sec.} \end{aligned} \quad (5-3)$$

Because the system responds slowly to the applied impulse, the maximum stored energy will be slightly less than that imparted by the impulse in accordance with the formula:

$$E = \frac{W^2}{2m} = \frac{(.025)^2}{2(3.667 \times 10^{-4})} = 0.8522 \quad (5-4)$$

Then energy is stored within a spring-mass system with spring constant k in accordance with:

$$E_s = \frac{1}{2} k x^2 \text{ or } = \frac{1}{2} k (\Delta r)^2. \quad (5-5)$$

Thus $E \approx E_s$ and

$$\begin{aligned} E &= 0.8522 = \frac{1}{2} (13,774) \Delta r^2 \\ \text{and} \\ \Delta r &= 11.12 \times 10^{-3} \text{ in.} \end{aligned} \quad (5-6)$$

This change in vessel wall radius then results in a stress of:

$$\sigma = E \frac{\Delta r}{r} = 30 \times 10^6 \frac{(11.12 \times 10^{-3})}{33} = 10113 \text{ psi.} \quad (5-7)$$

It should be emphasized that this is an ideal upper limit case and serves as a check on the more accurate calculation which predicts a maximum stress of 6,666 psi.

The equivalent static internal vessel pressure may then be calculated as:

$$P = \frac{\sigma t}{r} = \frac{6666(.5)}{33} = 101 \text{ psig} \quad (5-8)$$

It is therefore concluded that a wall response to the dynamic load will generate maximum wall stresses of approximately 6,600 psi. This same stress could be caused by a static internal pressure of 101 psig.

5.1.2 Determination of Design Pressure

It is important that a design pressure be established such that when a vessel is designed in accordance with that pressure value and the provisions of the ASME Section VIII code, it will also withstand the dynamic pressures of the DBA when applied as an accident case. It can be assumed that stresses in this accident case may reach 95% of material yield or 1.5 times the allowable working stress, whichever is less. Assuming that the allowable stresses are governed by ASME codes, we can use the 1.5 value in establishing a relationship between the ASME design pressure and the peak state equivalent of the dynamic load. The following consistent set of design values are recommended:

<u>Working Pressure</u> <u>ASME Section VIII</u>	<u>Static Accident</u> <u>Equivalent</u>	<u>Peak Dynamic</u> <u>Pressure DBA</u>
67 psig	101 psig	101 psia

It should be noted that the apparent similarity between the static accident equivalent and peak dynamic pressure DBA is circumstantial, and they are related only through the mechanical system upon which they act.

Thus to withstand the accident condition, a vessel must be capable of resisting a minimum pressure of 67 psi. A vessel with the dimensions used for this study, when designed for vacuum service, will have wall thickness of approximately 1/2 in. and can withstand an internal pressure of approximately 300 psi while remaining within the allowable operating stresses of the ASME code. It is, therefore, evident that such a vessel can readily resist the effects of the accident condition while maintaining a sizeable margin of safety.

5.2 Plenum

The vacuum pumps are connected to the vessel by a rectangular plenum. Should the DBA vapor-phase explosion occur, this plenum will be subjected to a pressure transient comparable to that previously described for the vessel wall.

The plenum should be designed with consideration of the DBA pressure transient. The structure should (1) remain within the elastic limit or (2) plastically deform in a predictable manner such that confinement integrity is guaranteed. As a possible third option, it may be permissible to allow the plenum to fracture, provided that personnel are protected. A shroud could be designed to contain any fracture fragments and limit contamination to a controlled region.

If in fact the plenum is a simple unsupported rectangular box, very little internal pressure is needed to cause the sides to plastically deform. A detailed analysis of such a structure would require use of a non-linear finite element stress analysis code. Such an effort is entirely feasible; however, it is beyond the scope of this present study.

It is suggested that the plenum walls could be strengthened by the addition of external "T" beam ribs. This type of structure is inherently rigid and could be designed to elastically withstand the DBA.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are drawn from this safety analysis:

- (1) It is highly unlikely that a vapor-phase explosion will occur as the result of an accidental cooling-water leak and mixing with the molten uranium; however, the design criteria should include such an accident contingency.
- (2) A one-dimensional, hydrodynamics computer code model of the vapor-phase explosion is sufficiently accurate for predicting the pressure transient experienced by the vacuum vessel wall, and this results in an exponential decay of 0.78 GPa(113 psi) peak and 500 μ s duration.
- (3) Fragments and missiles could potentially be produced as the vapor explosion shock wave impacts the various internal components in the vacuum vessel; however, analysis shows that they will not attain sufficient velocity to be a penetration threat to the vessel wall.
- (4) If the vapor-phase explosion is considered a threat of significance, the design criteria for the vacuum vessel should account for the realistically expected pressure transient on the vessel walls. Consequently, the design criteria for the vessel would be a working pressure of 67 psig (ASME Section VIII code) or 101 psig momentary single pulse equivalent static pressure.
- (5) From a cursory examination of the structural integrity of the plenum, it was obvious that the present flat plate rectangular design would be plastically deformed by the internal pressure of the DBA.
- (6) A more detailed analysis of the pressure vessel will be necessary for the region where the rectangular plenum is attached. This analysis should reflect those decisions and options selected for the final vessel configuration.

The following recommendations are offered:

- (1) The definitions of load severity and the safety factors permitted in the design of elements are affected by the hazard potential of the process materials. It is recommended that the DBA condition allow the vacuum vessel wall to sustain 1.5 times a working pressure (ASME Section VIII code) of 67 psig and still be less than 95% of yield; i.e., the vessel should contain the DBA pressure transient and still not exceed yield stress.
- (2) A safety analysis report (SAR) should be prepared to provide an evaluation of the potential hazards and the safety systems and design criteria that will tend to nullify these hazards by accident prevention or mitigation.
- (3) Either of two options are recommended for the designs of the vacuum vessel. These are Option 1: provide a sufficiently strong clamping mechanism to allow the vessel to withstand an internal static pressure of 101 psig. Option 2: allow the lid of the vacuum vessel to lift slightly to absorb the kinetic energy of the pressure impulse and to release the vapor phase explosion pressure. This option would require a deflector to eliminate the hazard from the escaping gases and to limit the spread of contamination.
- (4) The rectangular plenum should be designed to withstand the same internal dynamic pressure transient as the vacuum vessel without exceeding 95% of the material yield strength. If this cannot feasibly be accomplished with the material stresses remaining below the elastic limit, any plastic deformations must be predictable, and the resulting plastic deformation should not be permitted to cause a hazard to operating personnel.

7.0 REFERENCES

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APPENDIX A

ENGINEERING CALCULATIONS

EXPLOSION SOURCE PARAMETER DESCRIPTION

1. Quantity of Water

Maximum water flow rate $\cong$ 31 gal/min

$$\begin{aligned} &= 31 \text{ gal/min} \times \frac{3.7854 \text{ l}}{\text{gal}} \times \frac{1 \text{ min}}{60 \text{ s}} \\ &= 1.96 \text{ l/s} \end{aligned}$$

Assuming water flow for 1s before explosion,

total volume of water $\cong$ 1.96 l/s $\times$ 1s = 1.96l

$$= 1960 \text{ ml} = 1960 \text{ cm}^3 \text{ and}$$

water mass $\cong$ 1960 g.

Since

$$V = 4/3 \pi r^3, r = 7.76 \text{ cm} = 77.6 \text{ mm.}$$

2. Explosion Source

$$T_{\text{uranium}} \cong 2500^\circ\text{C} = 2773^\circ\text{K}$$

$$T_{\text{interface}} \cong 2113^\circ\text{C} = 2386^\circ\text{K}$$

$$70^\circ\text{C} \leq T_{\text{water}} \leq 2113^\circ\text{C}$$

The water can superheat to arbitrarily high temperatures depending upon the effective pressure. The most probable temperature of water in a freely contacting system (no externally applied pressure) corresponds to the spontaneous nucleation temperature which is approximately 305°C. The superheat energy can be approximated by

$$E \cong C_v \cdot \Delta T.$$

Thus

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$$E = 4.2 \text{ J/g}^\circ\text{K} \times (578^\circ\text{K} - 343^\circ\text{K}) = 987 \text{ J/g.} \quad (\text{A-1})$$

Applying a 50% efficiency factor to the expected superheat energy gives
maximum energy density = $987 \text{ J/g} \times 0.5 = 494 \text{ J/g}.$

The energy source for the explosion is then

$$E = 494 \text{ J/g} \times 1960 \text{ g} = 9.7 \times 10^5 \text{ J.} \quad (\text{A-2})$$

Initial pressure of the explosion source

$$P_i = 0.998 \text{ g/cm}^3 \times 0.019 \times 0.494 \text{ KJ/g} = 7787 \text{ psi} \cong 7800 \text{ psi}$$

Ambient pressure in vessel

$$P_a \cong 0.2 \text{ atm} = 2.9 \text{ psi.} \quad (\text{A-3})$$

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APPENDIX B

PAD CODE RESULTS

RUN2.STEAM - WATER VAPOR PHASE EXPLOSION TEST
VAPOR PHASE EXPLOSION TEST / TIME= 0.

PA03.6x

PAD Results For MARS Vapor Explosion
(t = 0.0 μs)

Figure B-1

RUN2.STEAM - WATER VAPOR PHASE EXPLOSION TEST
VAPOR PHASE EXPLOSION TEST / TIME= 0.

PAD3.5X

Figure B-1
(Cont.)

RUN2.STEAM - WATER VAPOR PHASE EXPLOSION TEST
VAPOR PHASE EXPLOSION TEST / TIME= 2.0000E+02

PAD Results For MARS Explosion
($t = 200 \mu s$)

Figure B-2

RUN2.STEAM - WATER VAPOR PHASE EXPLOSION TEST
VAPOR PHASE EXPLOSION TEST / TIME= 2.0000E+02

PABJ.6X

Figure B-2
(Cont.)

RUN2.STEAM - WATER VAPOR PHASE EXPLOSION TEST
VAPOR PHASE EXPLOSION TEST / TIME= 4.0000E+02

PAD Results For MARS Vapor Explosion
($t = 400 \mu s$)

Figure B-3

RUN2.STEAM - WATER VAPOR PHASE EXPLOSION TEST
VAPOR PHASE EXPLOSION TEST / TIME= 4.0000E+02

PA03.6X

Figure B-3
(Cont.)

RUN2.STEAM - WATER VAPOR PHASE EXPLOSION TEST
VAPOR PHASE EXPLOSION TEST / TIME= 6.0000E+02

PAD3.5X

PAD Results For MARS Vapor Explosion
(t = 600 μ s)

Figure B-4

RUN2.STEAM - WATER VAPOR PHASE EXPLOSION TEST
VAPOR PHASE EXPLOSION TEST / TIME= 6.0000E+02

PA03.6X

Figure B-4
(Cont.)

RUN2.STEAM - WATER VAPOR PHASE EXPLOSION TEST
VAPOR PHASE EXPLOSION TEST / TIME= 8.0000E+02

PA03.5x

PAD Results For MAPS Vapor Explosion
($t = 800$ μ s)

Figure B-5

RUN2.STEAM - WATER VAPOR PHASE EXPLOSION TEST
VAPOR PHASE EXPLOSION TEST / TIME= 8.0000E+02

PAD3.6x

Figure B-5
(Cont.)

RUN2.STEAM - WATER VAPOR PHASE EXPLOSION TEST
VAPOR PHASE EXPLOSION TEST / TIME= 1.0000E+03

PAD3.5x

PAD Results For MARS Vapor Explosion
($t = 1000 \mu s$)

Figure B-6

RUN2.STEAM - WATER VAPOR PHASE EXPLOSION TEST
VAPOR PHASE EXPLOSION TEST / TIME= 1.0000E+03

PA03.6x

Figure B-6
(Cont.)

RUN2.STEAM - WATER VAPOR PHASE EXPLOSION TEST
VAPOR PHASE EXPLOSION TEST / TIME= 1.2000E+03

PAD3.5X

PAD Results For MARS Vapor Explosion
(t = 1200 μs)

Figure B-7

RUN2.STEAM - WATER VAPOR PHASE EXPLOSION TEST
VAPOR PHASE EXPLOSION TEST / TIME= 1.2000E+03

PA03.6x

PAD Results For MARS Vapor Explosion
($t = 1200 \mu s$)

Figure B-7
(Cont.)

TABLE 2-1
(continued)

<u>Code/Standard</u>	<u>Area of Applicability</u>	<u>Condition</u>	<u>Design Requirements and/or Guidance</u>
ERDAM Appendix 6301 (Continued)	Unirradiated En- riched Uranium Storage Facilities (Continued)	Design Basis Accidents (Continued)	<p>The SAR shall assess natural forces pertaining to the site to define maximum credible natural events and consequent bases for design. To select design bases, existing historical data shall be examined in combination with safety factors consistent with the degree of potential hazard and with any uncertainties in defining design basis events such as natural phenomena, accident sequences, and the dispersal characteristics of any released material.</p> <p>In addition to normal dead and live loads, natural forces identified in the SAR such as floods, earthquakes, winds, and tornadoes shall be assessed in defining the design forces to be used in design.</p>
	Plutonium Facilities	Design Basis Accidents	<p>Critical items shall be designed to provide confinement of radioactive materials under normal operations and DBA conditions. In no case shall the applicable exposure regulations be exceeded either with respect to the operating personnel or to the public at the boundary. Consideration shall be given to the probability and effects of DBAs. Protection of employees within the facility shall be a consideration in all aspects of design.</p> <p>Structural design, including loading combinations and construction of critical safety and fire protection items, shall, as a minimum, be in accordance with pertinent nationally recognized codes and standards as referenced in ERDAM Appendix 6301, and the design criteria contained herein.</p>

TABLE 2-1

A SURVEY OF DESIGN REQUIREMENTS FOR PROJECTS WITH COMPONENTS AND SAFETY IMPLICATIONS RELATED TO THOSE OF THE MARS PROJECT

<u>Code/Standard</u>	<u>Area of Applicability</u>	<u>Condition</u>	<u>Design Requirements and/or Guidance</u>
ERDA 0531 Safety of Non-reactor Nuclear Facilities	Nonreactor Nuclear Facilities	Potential Significant Safety Hazards (assuming a release of a reasonable fraction of the nuclear material present) That Could Result in Any of the Following: <ol style="list-style-type: none"> 1. Radiation exposure in excess of established standards for offsite locations; 2. A significant hazard onsite due to exposure to radiation; 3. Significant property damage or loss onsite and/or offsite. 	<p>Conduct activities to assure:</p> <ol style="list-style-type: none"> 1. Identifiable risks no greater than those for comparable licensed nuclear facilities; 2. No undue risks to the health and safety of the public and employees. (Undue risk is defined as a level of identifiable risk that is unacceptable to ERDA/DOE.); 3. Protection of property and the environment from identifiable undue risks. <p>Prepare Operations Safety Requirements (OSRs) commensurate with the potential risks involved.</p> <p>Prepare a Safety Analysis Report (SAR) and include:</p> <ol style="list-style-type: none"> 1. Safety-related design criteria; 2. Evaluation of the risk associated with accidents from natural phenomena; 3. An evaluation of the engineered safety features to assure continued safe operation or safe shutdown under accident conditions; <p>Prepare Safety Assessment Document (SAD) and include assessment of the potential environmental, safety, and health (ES&H) risks or consequences if credible failures in safety systems and postulated operational errors occur. Include probable response to mitigate such accidents and their potential effects such that the probability of undue ES&H risks is precluded.</p>

TABLE 2-1
(continued)

<u>Code/Standard</u>	<u>Area of Applicability</u>	<u>Condition</u>	<u>Design Requirements and/or Guidance</u>
U.S. NRC Reg. Guide 1.48 Design Limits and Loading Combinations for Seismic Category I Fluid System Components (Continued)	Nuclear Power Plants (Continued)	Earthquake (Continued)	<p>Definitions:</p> <ol style="list-style-type: none"> 1. Allowable stress value (S) - as specified in Appendix I of Section III of the ASME Boiler and Pressure Vessel Code. 2. Emergency plant condition - those operating conditions that have a low probability of occurrence. 3. Faulted plant condition - those operating conditions associated with extremely-low probability postulated events. 4. Upset plant condition - those deviations from the normal plant condition that have a high probability of occurrence.

In the application of design limits, the design conditions should reflect the most adverse combination of loadings to which the components may be subjected. These limiting conditions correspond to low-probability postulated accidents or events.

Design limits for vessels are as follows:

1. ASME Code Class I Vessels.
 - a. Design limits specified as Level B Service Limits (NB-3223) in the ASME Code, Section III should not be exceeded when the component is subjected to concurrent loadings associated with either the normal plant condition or the upset plant condition and the vibratory ground motion of 50% of the SSE.
 - b. Design limits specified as Level C Service Limits (NB-3224) in the ASME Code should not be exceeded when the component is subjected to loadings associated with the emergency plant condition.

TABLE 2-1
(continued)

2-18

<u>Code/Standard</u>	<u>Area of Applicability</u>	<u>Condition</u>	<u>Design Requirements and/or Guidance</u>																																							
U.S. NRC Reg- Guide 1.76 Design Basis Tornado for Nuclear Power Plants	Nuclear Power Plants	Tornado	<p>Nuclear power plants must be designed so that the plants remain in a safe condition in the event of the most severe tornado that can reasonably be predicted to occur at a site. Nuclear power plants should be designed to withstand the Design Basis Tornado (DBT) defined below:</p> <table><tr><th rowspan="2"><u>Region</u></th><th><u>Maximum Wind Speed (mph)</u></th><th><u>Rotational Speed (mph)</u></th><th colspan="2"><u>Translational Speed (mph)</u></th><th><u>Radius of Maximum Rotational Speed (ft)</u></th><th><u>Pressure Drop (psi)</u></th><th><u>Rate of Pressure Drop (psi/sec)</u></th></tr><tr><th></th><th></th><th><u>Maximum</u></th><th><u>Minimum</u></th><th></th><th></th><th></th></tr><tr><td>I</td><td>360</td><td>290</td><td>70</td><td>5</td><td>150</td><td>3.0</td><td>2.0</td></tr><tr><td>II</td><td>300</td><td>240</td><td>60</td><td>5</td><td>150</td><td>2.25</td><td>1.2</td></tr><tr><td>III</td><td>240</td><td>190</td><td>50</td><td>5</td><td>150</td><td>1.5</td><td>0.6</td></tr></table>	<u>Region</u>	<u>Maximum Wind Speed (mph)</u>	<u>Rotational Speed (mph)</u>	<u>Translational Speed (mph)</u>		<u>Radius of Maximum Rotational Speed (ft)</u>	<u>Pressure Drop (psi)</u>	<u>Rate of Pressure Drop (psi/sec)</u>			<u>Maximum</u>	<u>Minimum</u>				I	360	290	70	5	150	3.0	2.0	II	300	240	60	5	150	2.25	1.2	III	240	190	50	5	150	1.5	0.6
<u>Region</u>	<u>Maximum Wind Speed (mph)</u>	<u>Rotational Speed (mph)</u>	<u>Translational Speed (mph)</u>		<u>Radius of Maximum Rotational Speed (ft)</u>	<u>Pressure Drop (psi)</u>	<u>Rate of Pressure Drop (psi/sec)</u>																																			
			<u>Maximum</u>	<u>Minimum</u>																																						
I	360	290	70	5	150	3.0	2.0																																			
II	300	240	60	5	150	2.25	1.2																																			
III	240	190	50	5	150	1.5	0.6																																			
			<p>These characteristics are identical to those specified in ERDM Appendix 6301, Part II, B for Plutonium Facilities.</p>																																							
ASME Boiler and Pressure Vessel Code, Section III	Pressure Vessels	General Guidelines	<p>The design shall be such that stress intensities will not exceed the limits specified for the particular material in use. For Type 304 stainless steel plate, the design stress intensity values, S_m, as a function of temperature, are as follows:</p> <table><tr><th rowspan="2"><u>Minimum Yield Strength (ksi)</u></th><th rowspan="2"><u>Minimum Ultimate Tensile Strength (ksi)</u></th><th colspan="10"><u>Design Stress Intensity (S_m), ksi, for Metal Temperatures, °F, not to Exceed</u></th></tr><tr><th><u>100</u></th><th><u>200</u></th><th><u>300</u></th><th><u>400</u></th><th><u>500</u></th><th><u>600</u></th><th><u>650</u></th><th><u>700</u></th><th><u>750</u></th><th><u>800</u></th></tr><tr><td>30.0</td><td>75.0</td><td>20.0</td><td>20.0</td><td>20.0</td><td>18.7</td><td>17.5</td><td>16.4</td><td>16.2</td><td>16.0</td><td>15.6</td><td>15.2</td></tr></table>	<u>Minimum Yield Strength (ksi)</u>	<u>Minimum Ultimate Tensile Strength (ksi)</u>	<u>Design Stress Intensity (S_m), ksi, for Metal Temperatures, °F, not to Exceed</u>										<u>100</u>	<u>200</u>	<u>300</u>	<u>400</u>	<u>500</u>	<u>600</u>	<u>650</u>	<u>700</u>	<u>750</u>	<u>800</u>	30.0	75.0	20.0	20.0	20.0	18.7	17.5	16.4	16.2	16.0	15.6	15.2					
<u>Minimum Yield Strength (ksi)</u>	<u>Minimum Ultimate Tensile Strength (ksi)</u>	<u>Design Stress Intensity (S_m), ksi, for Metal Temperatures, °F, not to Exceed</u>																																								
		<u>100</u>	<u>200</u>	<u>300</u>	<u>400</u>	<u>500</u>	<u>600</u>	<u>650</u>	<u>700</u>	<u>750</u>	<u>800</u>																															
30.0	75.0	20.0	20.0	20.0	18.7	17.5	16.4	16.2	16.0	15.6	15.2																															

TABLE 2-1
(continued)

Code/Standard	Area of Applicability	Condition	Design Requirements and/or Guidance											
ASME Boiler and Pressure Vessel Code, Section VIII, Division 1	Pressure Vessels	General Guidelines	The maximum allowable tensile stress, S, permitted for 304 stainless steel plate, as a function of temperature, is as follows											
			Specified Minimum Yield (ksi)	Specified Minimum Tensile (ksi)	Maximum Allowable Stress (S), ksi, Metal Temperatures, °F, not to Exceed									
					100	200	300	400	500	600	650	700	750	800
			30.0	75.0	18.8	15.7	14.1	12.9	12.1	11.4	11.2	11.1	10.8	10.6

The minimum thickness or maximum allowable working pressure for cylindrical shells under internal pressure shall be the greater thickness or lesser pressure as given by (1) or (2):

Circumferential Stress

$$t = \frac{PR}{SE - 0.6P} \quad \text{or} \quad P = \frac{SEt}{R + 0.6t} \quad (1)$$

when the thickness does not exceed one-half of the inside radius, or P does not exceed 0.385 SE, or

Longitudinal Stress

$$t = \frac{PR}{2SE + 0.4P} \quad \text{or} \quad P = \frac{2SEt}{R - 0.4t} \quad (2)$$

when the thickness does not exceed one-half of the inside radius, or P does not exceed 1.25 SE,

where

t = minimum required thickness, in.,

R = inside radius,

S = maximum allowable stress value, psi., and

E = joint efficiency.

OPERATING CONDITIONS

1. Chamber Pressure $\sim 10^{-6}$ Torr
2. Crucible Cooling ~ 150 gpm at 80 psi
3. Vapor Shield Cooling ~ 80 gpm at 80 psi
4. Electron Gun Cooling ~ 40 gpm at 80 psi

MARS Chamber Configuration

Figure C-1

PAD Calculational Geometry

Figure 3-2

Pressure - Time History At Vacuum Vessel Wall
Figure 3-3

Time = 200 μ s

Time = 400 μ s

Time = 600 μ s

Time = 800 μ s

Vapor Phase Explosion Pressure Profiles -
Prior To Wall Contact

Figure 4-2