STAR Mechanical Design Standards and Guidelines

Introduction

The purpose of this note is to outline, in a single document, the mechanical design standards or guidelines that will be used in designing the STAR Detector for RHIC. The following is a brief summary of the kind of guidance most mechanical engineers/designers should be looking for early in the design process. For reasons ranging from RHIC safety requirements to common sense, the following information should be understood and kept in mind.

Institutional Standards

When specific institutional design standards or guidelines exist, they should be used. The guidelines outlined in this note are not meant to replace but instead to supplement existing guidelines. Most equipment that is built for STAR will be used or tested at your home institution and at RHIC at some point in its life cycle. Both BNL and RHIC have some guidelines in this area. Your home institution may have some guidelines of its own. Where more than one set of guidelines exist, use whichever are more stringent, your home institution or BNL/RHIC's. Appendix A lists the BNL and RHIC manuals where design standards information can be found. Where no specific guidelines exist, use the guidelines outlined in this note.

Design Loads

In your structural analyses, take handling, transportation and assembly loads into account as well as thermal expansion caused by potential temperature fluctuations (e.g., during shipping the temperature may range from freezing to 140 °F). One of these "other" loads may well be the limiting or design load. BNL has specific seismic requirements for experimental equipment. These are documented in STAR Note 140. To summarize the requirements – all equipment that is to be used in any capacity at BNL should be designed to withstand at least 0.15 g horizontal load. (Note that it is also sensible practice to design a small amount of horizontal load carrying capability (at least 0.10 g) into stands and equipment, even if there are no documented requirements to do so, for basic stability.)

Materials Data

There are many sources of data on materials – manufacturers handbooks such as the Alcoa Handbook (reference 1) and the appendices of many textbooks. There are also a couple of government publications compiled from materials test data taken over many years. One of these that may well be worth investigating is the *Military Standardization Handbook on Metallic Materials and Elements for Aerospace Vehicle Structures* or *MIL–HDBK–5D* (reference 2). This is a very worthwhile two volume set that includes data for many standard materials as

well as for many alloys and exotics. It also includes properties over a wide range of temperatures.

Analysis Methods

The applicable safety margins or factors depend on the type of load(s) and how well they can be estimated, how boundary conditions have been approximated, as well as how accurate your method of analysis allows you to be.

Bounding Analyses

Bounding analyses or rough scoping analyses have proven to be valuable tools. Even when computer modeling is in your plans, a bounding analysis is a nice check to help avoid those "dumb" mistakes. Sometimes bounding analyses are sufficient. An example of this would be for the case of an assembly fixture where stiffness is the critical requirement. In the case where deflections must be so low that the element is over–designed in terms of stress by a factor of 10 or more, a crude estimation of stress may suffice.

Handbook Approximations or Closed–Form Analytical Solutions – e.g., *Formulas for Stress and Strain* by Roark and Young (reference 3). Many times, when boundary conditions and applied loads are simple to approximate, a handbook or closed–form solution can be found or developed. For the majority of tooling and fixturing and even some non–critical experimental equipment, these types of analyses are sufficient. Often, one of these formulas can be used to give you a conservative solution very quickly, or a pair of formulas can be found which represent upper and lower bounds of the true deflections and stresses.

Finite Element Analyses

When the boundary conditions and loads get complex, or the correctness of the solution is critical, computer modeling is often called for. If this is the case, there are several simple rules to follow, especially if you are not intimately familiar with the particular code or the application.

1) Always bound the problem with an analytical solution or some other approximate means.
2) If the component is critical, check the accuracy of the code and application by modeling a similar problem for which you can find an analytical or handbook solution.
3) Find a qualified person to review your results.
4) Document your assumptions and results.

Failure Criteria

The failure criteria chosen depends upon the application. Many factors such as the rate or frequency of load application, the material toughness (degree of ductility), the human or monetary risk of component failure as well as many other complications must be considered.

Brittle materials (under static loads, less than 5 % yield prior to failure)
This includes ceramics, glass, some plastics at room temperature, some cast metals, and many materials at cryogenic temperatures. The failure criteria chosen depends on many factors so use your engineering judgment. In general, the Coulomb–Mohr or modified Mohr theory should be employed (references 3 & 4).

Ductile materials (under static loads, greater than 5% yield prior to failure)
Includes most metals and plastics, especially at or above room temperature. The failure criteria chosen again ultimately rests with the cognizant engineer because of all the adverse factors that may be present. In general though, the Distortion–Energy Theory, or von Mises–Hencky theory (von Mises stresses), is most effective in predicting the onset of yield in materials. The Distortion Energy Theory states that elastic failure occurs when:

$$2\,\sigma_y^2 = (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2$$

where σy = stress at yield and σ_1, σ_2 and σ_3 are the 3 principle stresses in a triaxial stress state.

Slightly easier to use and always conservative is the maximum–shear–stress theory. For further discussion, see references 3 and 4.

Factor/Margin of Safety
Some institutions may have published guidelines which specifically discuss factors or margins of safety for various applications. For the cases where specific guidelines do not exist, the following may be used (subject to common sense).

Factor of safety
Simplistically, if F is the applied load (or σ the applied stress), and F_f is the load at which failure occurs (σ_f the stress at which failure occurs), we can define the factor of safety (F.S.) as:

$$\text{F.S.} = \frac{F_f}{F} \quad \text{or} \quad \frac{\sigma_f}{\sigma}$$

Margin of safety
Margin of safety, or M, is defined as:

$$M = \text{F.S.} - 1$$

The word failure, as it applies to engineering elements or systems, can be defined in a number of ways and depends on many factors. Discussion of failure criteria

is presented in the above section, but for the most common cases in STAR will be the load or stress at which yielding begins.

Specific Guidelines for STAR

Factors of Safety for various types of equipment are presented in table 1.

Lifting & handling fixtures, shipping equipment, test stands, and fabrication tooling

In situations such as these, where weight, size and material thickness do not affect the physics capabilities of the detector, the appropriate F.S. should be at least 3. When human safety is potentially at risk, a factor of 5 may be more appropriate. Note that since the vast majority of this type of equipment is designed using ductile materials, for good reason, these F.S.'s apply to the material yield point.

Experimental hardware that does not present a human, or significant cost/schedule risk if failure occurs

In situations such as these, especially where there is the potential for an increase in physics capabilities, the F.S. may be as low as 1.5. Many factors must be taken into account if a safety factor this low is to be employed: a complete analysis of worst case loads must be done; highly realistic or else conservative boundary conditions must be applied; the method of analysis must yield accurate results; reliable materials data must be used or representative samples must be tested. In other words, if F.S.'s this low are utilized, the analysis and assumptions must be highly scrutinized.

Table 1

Type of Equipment	Minimum F.S.	Notes
Lifting and handling equipment	3 – 5	Where there is a risk to human safety or to costly equipment, choose F.S. closer to 5.
Test stands, shipping and fabrication fixtures	3	
Experimental equipment	1.5 – 3	1.5 is allowable if req'd for physics capability reasons and the analysis method is highly refined.

Documentation

It is not only good engineering practice to document your analyses, but it is extremely beneficial for other reasons as well. These benefits include: the fact that you may forget what you did a couple of years from now; it is often very beneficial to have someone else review your work for errors; the fact that someone else will likely operate and upgrade this equipment after you are no longer associated with it; and the fact that it is required by RHIC and therefore STAR for our Quality Assurance program, safety reviews, operations and upgrade programs. For these reasons, all major components of the STAR detector will have their engineering analyses documented as STAR Notes. Utilize your institutional documentation formats or use the following guidelines. The following minimal list of topics should be covered in all forms of engineering analysis documentation:

1) Introduction, Background and Purpose
2) Applicable Requirements, Standards and Guidelines
3) Assumptions (boundary conditions, loads, simplifications, etc.)
4) Analysis Method (closed form, handbook formulas, computer modeling, etc.)
5) Results (including factors of safety and location/name of critical element)
6) Discussion (level of conservatism, limitations, cautions, etc.)
7) References (STAR Notes, textbooks, handbooks, computer programs, etc.)

References:

1 – Alcoa Handbook of Design Stresses for Aluminum, Aluminum Company of America, Pittsburgh, PA

2 – Military Standardization Handbook, Metallic Materials and Elements for Aerospace Vehicle Structures, MIL–HDBK–5D. Copies can be obtained from: Naval Publications and Forms Center, 5801 Tabor Ave, Philadelphia, PA

3 – Formulas for Stress and Strain, R. J. Roark and W. C. Young, McGraw–Hill Book Co.

4 – Mechanical Engineering Design, J. E. Shigley, McGraw – Hill Book Co.

Appendix A

Relevant BNL & RHIC policies, guidelines and information sources–

1) BNL Environmental Safety and Health (ES&H) Standards
2) RHIC/BNL Safety and Environmental Administrative Policy and Procedures Manual (SEAPPM)
3) RHIC Operations Procedures Manual
4) DOE Order 6430.1A General Design Criteria
5) National Fire Protection Association 101 (NFPA 101)
6) National Electrical Code (NEC)
7) RHIC Experiment Safety Committee (ESC) Chairman

Copies of items 1 and 2 are available at BNL and at LBL in the STAR Project Office. Access to item 3 will be available shortly (electronically...) Items 4–6 are most likely available at your home institution; if not, they are available at BNL and LBL.