CHAPTER 4

LOADING COMBINATIONS

4-1. General. Arch dams are designed for the same loads as other dams with the exception of the temperature load which has a significant influence in arch dam design as compared to gravity dam design. The loads for which an arch dam must be designed are as follows:

a. Dead Load. Dead load is due to the weight of the concrete plus the appurtenant structures. The unit weight of the concrete is based on the laboratory test results of the mix design; however, for preliminary design a unit weight of 150 pounds per cubic foot (pcf) can be used. The weight of the appurtenances is normally negligible compared to the weight of the dam and may be neglected in static design. In the case of a massive, overflow-ogee-weir spillway or massive outlet works, it may be prudent to include these structures in the finite element model used for static and dynamic analyses.

b. Temperature Load. The temperature load results from the differences between the closure (grouting) temperature and concrete temperatures in the dam during its operation. The closure temperature is the concrete temperature at the time of grouting of the contraction joints. This temperature, which in effect is the datum for all the future temperature loading, is determined from the results of the stress analyses of the dam under different loading combinations. Another way to describe the closure temperature may be to consider it as a stress-free temperature (only for dams that are grouted). For example, if an arch dam is grouted at 55 °F, there will not be any stresses due to the temperature loading in the dam as long as the operating temperature of the dam remains at 55 °F. However, once the concrete temperature exceeds 55 °F, the resulting positive temperature loading will cause compressive stresses in the arches which in turn result in deflection into the reservoir. The opposite is true when in the winter the concrete temperature goes below 55 °F. In this case, the arches will experience tension which would cause deflection downstream. The selection of the closure temperature usually involves a compromise between the ideal stress distribution in the dam and practical considerations such as the feasibility of achieving the desired closure temperature. The closure (grouting) temperature is one of the most important construction parameters in arch dams because once the monolith joints are grouted, the structure is assumed to become monolithic and the arch action begins. Following the determination of the closure temperature, the individual blocks should be sized to prevent cracking during construction and to provide satisfactory contraction joint opening for grouting.

(1) The following hypothetical example may help explain the role of the temperature load - and that of the closure temperature - in arch dams. Consider an arch dam to be designed for a site with uniform air and water temperatures of 65 °F, i.e., no seasonal cyclic temperature changes in the air and reservoir. Neglecting the effect of the solar radiation, the operational concrete temperature is then the same as that of the air and reservoir: 65 °F. It is further assumed that there is no fluctuation in the reservoir level, so the dam is subjected to the full reservoir load at all times. Since the hydrostatic load in this example produces large tensile stresses along the heel of the cantilevers, the design objective would be to counteract the

tensile stresses by introducing a large temperature load which would cause the cantilevers to deflect into the reservoir. This objective can be accomplished by choosing the lowest possible closure temperature - say 35 ^{o}F - which would result in a 30-^{o}F (65 ^{o}F - 35 ^{o}F) temperature load.

(2) As seen in the simplified example, the closure temperature is a design parameter which, within certain constraints, can be selected to help achieve desirable stress distribution in arch dams; thus, it has an effect on the geometry, i.e., the vertical and horizontal curvatures of the dam. Figure 4-1 shows the relationship between the closure temperature and the operating concrete temperatures which comprise the temperature loading as used for the Portugues Dam, Ponce, Puerto Rico.

c. Hydrostatic Load. The reservoir load is based on a study of the reservoir operation. Unlike a gravity dam for which higher reservoir levels would result in more critical cases, an arch dam may experience higher tensile stresses (on the downstream face) under low reservoir elevations. Studies of the reservoir operation should include the frequency of occurrence and duration of reservoir stages and the time of the year in which different water stages occur. These data are used in conjunction with the appropriate temperature information as shown in Figure 4-2 (see Chapter 8 for temperature study).

d. Earthquake Load. For arch dams in earthquake zones, two levels of earthquakes should be used. These are the Operational Basis Earthquake (OBE) and the Maximum Design Earthquake (MDE). OBE is defined as a ground motion having a 50 percent chance of exceedance in 100 years. The dam is expected to respond elastically under the OBE (assuming continuous monolithic action along the entire length of the dam). MDE is the maximum level of ground motion for which the arch dam should be analyzed, and it is usually equated to the maximum credible earthquake (MCE). MCE is defined as the largest reasonable possible earthquake that could occur along a recognized fault or within a particular seismic source. If dam failure poses no hazard to life, an MDE lower than MCE level of motion may be specified. Under the MDE, the dam is allowed to respond nonlinearly and incur significant damage, but without a catastrophic failure in terms of loss of life or economics. Close coordination should be maintained with HQUSACE (CECW-ED) during the selection process of earthquake ground motions for arch dams.

e. Miscellaneous Loads. Where applicable, loads due to ice and silt should be included in the design of an arch dam. In the absence of design data, an ice load of 5 kips per linear foot of contact along the axis may be assumed. The silt load should be determined from the results of the sedimentation study for the dam. If these loads are small compared to the other loads, they can be neglected at the discretion of the designer.

4-2. Loading Combinations. Arch dams are designed for two groups of loading combinations. The first group combines all the static loads and the second group takes into account the effects of earthquake. Depending on the probability of occurrence of the cases in each group, they are labeled as Usual, Unusual, and Extreme loading cases. It must be stressed that each dam is a unique structure, and there are many factors to consider when deciding on the loading combinations. Factors such as climatic conditions, purpose of reservoir, spillway usage, operation of reservoir (as designed and anticipated

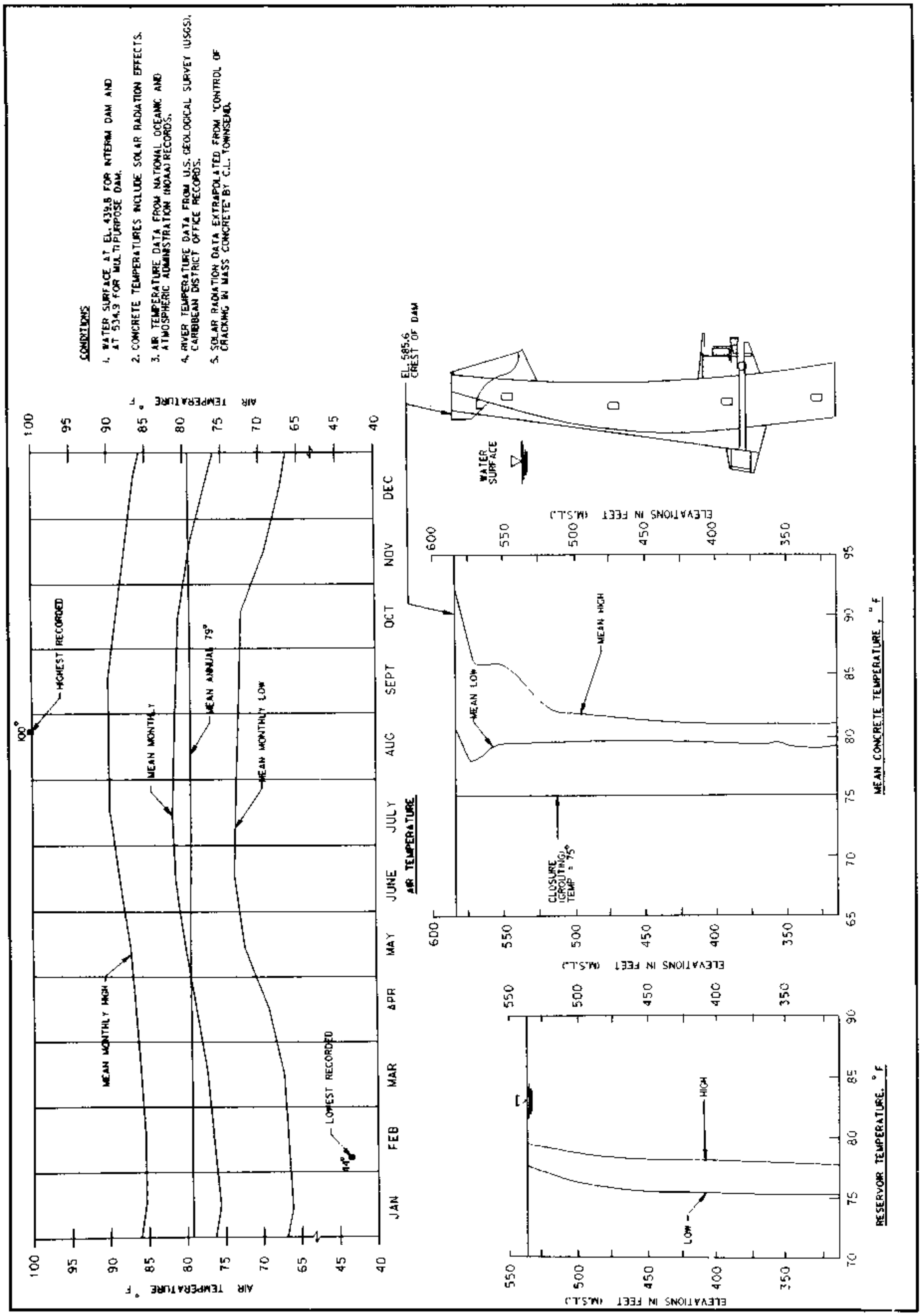

Figure 4-1. Mean concrete temperature

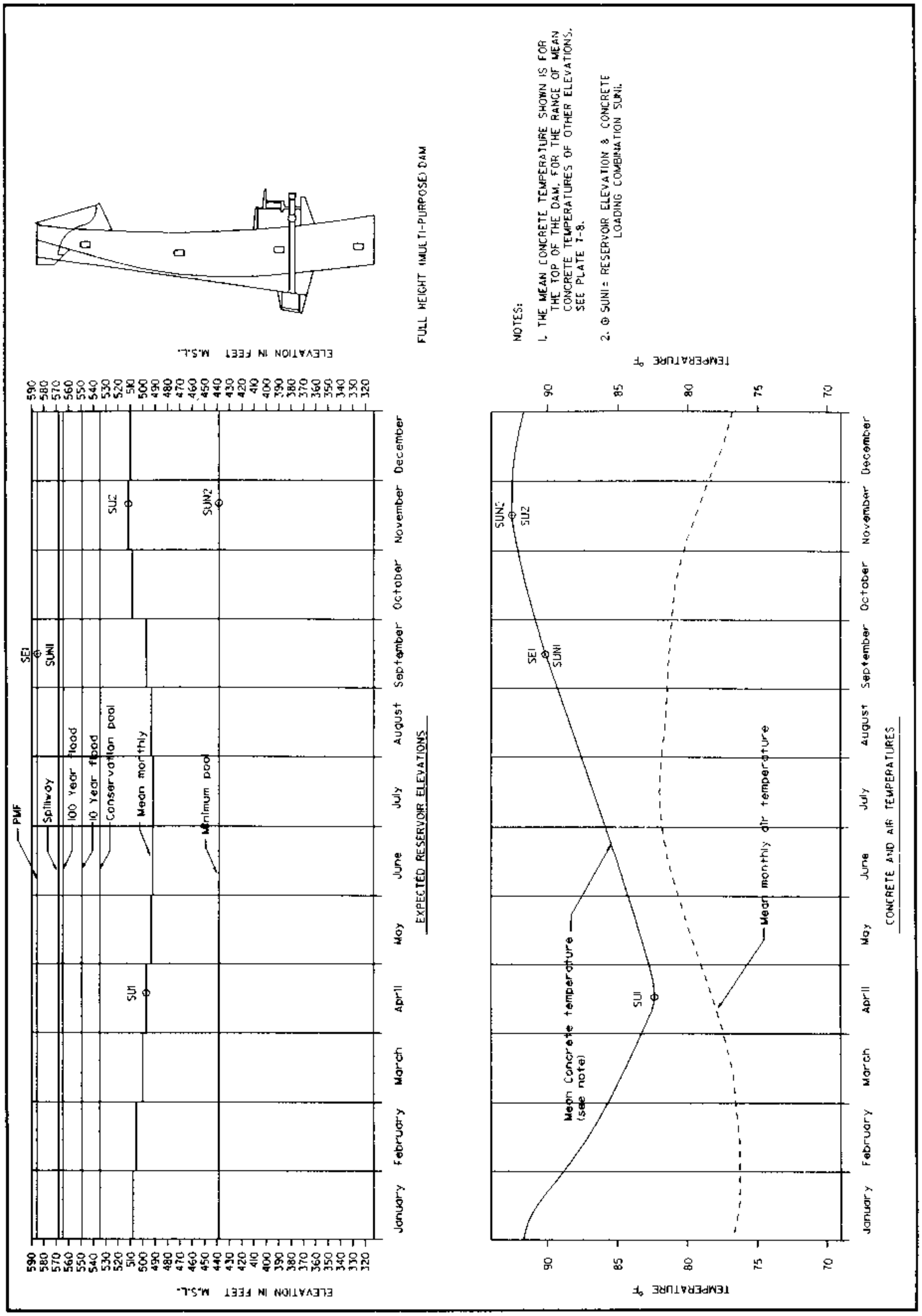

Figure 4-2. Reservoir elevations, mean concrete and air temperatures

actual), and location have direct bearing on the approach taken in determining and combining the loads and the classification of the loading combinations. Figure 4-2 illustrates the selection of the loading combinations for the Portugues Dam, Ponce, Puerto Rico. Tables 4-1 and 4-2 present the static and dynamic loading combinations which must be investigated as a minimum. The allowables and factors of safety are discussed in Chapter 11.

4-3. Selection of Load Cases for Various Phases of Design.

a. Reconnaissance. No detailed design is required during reconnaissance studies. The study in this phase is limited to the volume computation as discussed in Chapter 6 for the purpose of comparative studies with other types of dams. Of course, it is assumed that a suitable site exists for an arch dam based on the geometry of the site and the type of foundation material.

b. Feasibility. Limited design work should be accomplished during this phase of the design. From the results of the basic hydrology study, the preliminary loading combinations should be established and the temperature loading on the dam should be estimated from a study of similar projects. Basic dimensions of the dam should be determined using the procedure discussed in Chapter 6 to the extent necessary to obtain the data required for stress analysis. Only a static design analysis using two opposing loading combinations is required at this time. Based on the results of the stress analysis, a number of trials and adjustments in the geometry may be required to obtain acceptable stress distribution throughout the dam.

c. Preconstruction Engineering and Design (PED). Detailed design and analysis of the dam are to be performed during the PED phase with the results presented in various Feature Design Memoranda (FDM). The load cases must be established at the earliest stages of this phase. The temperature loading needs to be determined from the results of the temperature study which is initiated at beginning of PED, and the final reservoir elevations, their durations, and the time of year in which these reservoir stages are expected must be determined in order to develop the loading combinations as shown in Figure 4-2. The selection of the loads for the loading combinations should be given careful consideration. As an example related to Figure 4-2, it is considered prudent to select the middle of September for the probable maximum flood (PMF), although theoretically the PMF could happen at any time during the 12-month cycle. The rationale is that it is more likely for the PMF to occur in the middle of the wet season - for this particular site - than any other time. The significance of the above example is in the "concrete temperature occurring at that time," in accordance with case SE1, Table 4-1. If the PMF is assumed to happen in April when the mean concrete temperature is at its lowest, there would be a very small temperature on the dam (as shown by the closure temperature and the mean low concrete curve in Figure 4-1) which would result in too much conservatism. The opposite would be true if the PMF is assumed in November.

TABLE 4-1

Static Loading Combinations

Static Usual (SU)

SU1: Minimum usual concrete temperature.
Reservoir elevation occurring at that time. Dead Load.

SU2: Maximum usual concrete temperature.
Reservoir elevation occurring at that time. Dead Load.

SU3: Normal Operating Reservoir Condition.
Concrete temperature occurring at that time. Dead Load.

Static Unusual (SUN)

SUN1: Reservoir at spillway crest elevation.
Concrete temperature at that time. Dead Load.

SUN2: Minimum design reservoir elevation.
Concrete temperature occurring at that time. Dead Load.

SUN3: End of construction condition. Structure completed, empty reservoir. Temperature Load.

Static Extreme (SE)

SE1: Reservoir at Probable Maximum Flood (PMF) elevation. Concrete temperature occurring at that time. Dead Load.

TABLE 4-2

Dynamic Loading Combinations[1]

Dynamic Unusual (DUN)

DUN1: Operating Basis Earthquake (OBE) plus static load case SU3.

DUN2: OBE plus static load case SUN3.

Dynamic Extreme (DE)

DE1: Maximum Design Earthquake (MDE) plus static load case SU3.

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[1] See Chapter 11 for guidelines for treatment of dynamic response of the dam.