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MATERIALS PERFORMANCE IN THE SOLAR CENTRAL RECEIVER PILOT PLANT

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ABSTRACT

The 10 MW_e Solar Central Receiver Pilot Plant, which is to be built at Barstow, California, is designed to provide development, fabrication, and operating data necessary to demonstrate the technical feasibility of the solar central receiver concept. The Pilot Plant consists of approximately 2000 reflecting heliostats which redirect solar insolation to a central receiver mounted on a tower. The energy collected by the receiver is used to produce superheated steam which is then used to generate electricity and/or charge storage. Performance of the plant will be studied during a five year test period scheduled to begin December 1981. The plant is being designed for a thirty year life. For the Pilot Plant, successful performance requires materials having not only the proper initial properties, but also having long-term stability in the presence of thermal, chemical, and mechanical environments. For purposes of this discussion materials concerns are categorized into four operating subsystems of the plant: collectors, receiver, storage, and electrical power generation.

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MATERIALS PERFORMANCE IN THE SOLAR CENTRAL RECEIVER PILOT PLANT

Introduction

The Solar Thermal Central Receiver program of the Department of Energy has for its objectives to harness solar thermal energy for generation of electricity, either monolithic or in combination with fossil power, and also to develop process heat applications for solar thermal energy. The aim is to develop solar thermal systems to the status of alternative energy sources for utilities by the mid 1980's, and to achieve economic competetiveness with fossil and nuclear plants by the 1990's.[1] The first electricity to be generated in the program will come from the ten megawatt pilot plant which is nearing the start of construction in Barstow, California. Funding for the project is being provided by the Department of Energy, Southern California Edison Company, Los Angeles Department of Water and Power, and the California Energy Commission. When completed in 1981, the plant will be tied into the regional grid and operated by S. C. E. The pilot plant program will provide some of the development, production, operation and maintenance data necessary to evaluate the commercial potential of the concept.

Sandia Laboratories provides technical program management and supporting R&D for the Department of Energy in the systems application of central receiver technology. The Barstow Pilot Plant represents the first full scale U. S. application of the technology and as such is a critical gate in the development program. The final design for Barstow is being conducted by an industrial team led by McDonnell Douglas Astronautics Company. That design will be based upon tradeoff studies and experiments conducted in support of the program. This paper summarizes these studies in the area of materials performance and describes the emerging technology.

For the central receiver concept embodied by the pilot plant,[2-5] a 100-acre field of sun-following mirrors, or heliostats, will be employed to collect and concentrate the sun's rays onto a receiver located atop a 90-meter tall central tower. An artists' representation of the completed plant is displayed in Figure 1. The collector field will consist of approximately 2000 heliostats, each with roughly 40 square meters of reflecting surface. At the receiver, the concentrated incident energy is absorbed to produce superheated steam from water which passes vertically through an array of tubes mounted on the outside of the structure. The incident energy density is over 300 suns, enough to melt the metal tubes in the absence of coolant flow. In order to track the sun during the day and quickly defocus the field if water flow is interrupted, the heliostat field will be computer-controlled. Superheated steam passes from the receiver to a turbine located on the ground, and to storage. The storage subsystem is designed to permit generation of 7 megawatts of electricity for up to four hours without sunlight.

In keeping with the philosophy for conventional power plants, the pilot plant is being designed to have a thirty-year operating life; the first five years will be devoted to intensive testing and evaluation. Although the water/steam energy transport concept was chosen because the technology is familiar from fossil power plants, there are several features inherent to solar energy which make the pilot plant, or any solar plant, a venture into new territory. The substance of this paper is a discussion of the challenges which have faced the designers and materials engineers who have worked on the project, plus summaries of the studies which have been conducted to answer the questions. The plant incoporates four major subsystems, as shown in Figure 2(2). In order of energy flow the subsystems are: collectors, receiver, storage, and electrical generation. The unique materials concerns will be presented for each subsystem in the same order.

Collector (heliostat) Subsystem

The long-run success of the solar central receiver program depends in large measure upon development of reliable, low-cost heliostats. We say this because the heliostats are so numerous, and their operating requirements are so exacting, that they could embody nearly one-half of the capital cost of solar thermal power plants. The design goal for the pilot plant heliostats is to maintain overall reflectivity to the solar spectrum of 85 to 87 percent over their operating life.(2) Toward this end environmental protection of the reflecting surfaces is provided through utilization of the "second surface" concept, and by stowing the heliostats in an inverted position. A prototypical heliostat is shown in Figure 3. For purposes of discussion we shall discuss the materials topics for the heliostats in three categories: structural rigidity, reflectivity, and glass integrity. In the next paragraphs each of these categories will be treated in turn.

Good collection efficiency requires that the mirror not develop a convex shape even under severe operating conditions (i.e., wind and temperature excursions). The goal is to maintain an angle-of-reflection error less than a few milliradians in a 27 mph (13 m/s) wind, and for the assembly to survive a 90 mph (40m/s) wind.(1) To achieve the required rigidity while maintaining lightness for tracking and stowing, a typical heliostat likely will incorporate six rectangular mirrors fabricated from one-eighth inch thick float glass and bonded with polyurethane adhesive to a two-inch thick polystyrene foam/sheet steel sandwich. The edges are sealed with silicone rubber. The composite is designed with a slight concave shape, so that at the lowest operating temperature (-20°F) it does not defocus by going convex; conversely, at the highest temperatures (+ 120°F), the focal length shortens. The mirrors must withstand cold water shock due to washing or sudden rain, and resist accumulative curvature due to creep of the polymers during the thermal cycles. In addition to wind loads, the structure must withstand ice and snow loads, and earthquake shocks to 0.25 g. Full-scale laboratory tests have demonstrated(6) that all of these structural goals are achieved by the design described above.

In the interior of the glass, absorption losses, which are most often due to the pressure of iron impurities, can degrade the optical performance significantly.(7-9) Float glass normally contains iron in both the Fe^{2+} and the Fe^{3+} valence state; however, the Fe^{2+}, which absorbs in the infrared portion of the solar spectrum, is the primary offender. Mirrors fabricated from commercial float glasses, which contain ~ 0.08 wt. pct. Fe (expressed as Fe_2O_3), will absorb as much as eighteen percent (nine pct. per pass) of the reflected solar energy. Reduction of absorption losses offers opportunity for significant performance improvement; therefore, a major objective for pilot plant heliostat design has been to minimize absorbtion losses in the bulk glass.

Improved bulk transmissivity can be achieved by (a) using thinner glass; (b) specifying highly oxidized glass ($Fe^{3+}/Fe^{2+} > 1$); and (c) employing low-iron glass. Economics and fabricability studies have led to a combination of (a) and (c) for the pilot plant heliostat glass. "Normal" float glass is ~ 0.28 in. (7 mm) thick. Large reductions from this thickness will degrade the optical qualities due to fabrication difficulties, and also reduce the mechanical strength of the mirrors. Therefore, specifications were written which call for 0.100 in. (2.54 mm) glass thickness, thin enough to significantly reduce transmission losses yet not so thin as to compromise mechanical strength or optical quality. Specification of low-iron float glass (0.044 wt. pct. Fe expressed as Fe_2O_3) will further reduce absorbtion losses in the new mirrors. Recent measurements made on samples of the glass purchased for the pilot plant have indicated that the supplier has exceeded the transmissivity spec. of 0.89 and has produced low iron float with transmissivity of 0.91. Furthermore, studies at Sandia Laboratories have shown that photoinduced changes (solarization) to the bulk glass during field exposure may actually improve this figure.(9) Considerable scientific interest has been generated in attempting to identify the precise mechanisms for the improvement.

Normal processes for cutting glass for mirrors leaves rough edges which contain microscopic flaws. In the presence of moisture and under the action of thermal stresses, residual stress, or hailstone impacts, these flaws conceivably could grow. Performance in this area can be improved by thermally polishing the cut surfaces, or employing special cutting procedures; and the need for such procedures is being evaluated (10). If glass for the mirrors can be fabricated to heliostat size, no cutting will be necessary. With regard to mechanical damage, specifications call for the glass to survive multiple impacts of 3/4-inch diameter hailstones moving at 65 fps. In laboratory tests, the mirrors withstood this impact, although they were damaged by the impact of one-inch hailstones moving at 75 fps.(6)

Because float glass is produced by floating the molten glass on a molten tin bath, the finished glass incorporates both a tin-poor and a tin-rich surface. Accelerated environmental studies have shown that the tin-rich surface is significantly more resistant to the weathering which can occur under the combined action of moisture (e.g. from dew) and dissolved minerals (e.g., soluble alkalis from dust).[11, 12] Even in the absence of alkalis, exposure to very high humidity (98% RH) at temperatures of 50-80°C in laboratory tests results in the formation of a translucent film on the surface of the glass. This film, which is ~ 0.2 μ thick, probably results from the interdiffusion of sodium from the glass and hydrogen from the water film. The film behaves as an antireflection coating, however, and is not degrading to mirror performance. If the accelerated tests continue for extended periods, the film ultimately transforms to a white layer which does degrade performance. However, because the laboratory tests are so greatly accelerated, no evidence generated to date suggests that a front surface weathering problem of the magnitude deserved in the laboratory tests will occur in the field within the design lifetime of the plant. One design spec which has emerged from these tests calls for the pilot plant mirrors to be silvered on the tin-poor surface, thereby leaving the chemically more durable surface exposed to the atmosphere.

The front (first) surface of the mirrors can be degraded by mechanical as well as chemical means. Dust storms can produce abrasion, and, again, laboratory studies have shown that the problem could be serious; dirt buildup could reduce reflectance more than 25 percent within short periods of time.[12] Humidity amplifies the buildup rate, apparently by promoting physical-chemical bonds between particle and surface. In the field, however, rain and frost will clean the surface, and in fact, frost is a very effective cleaner (8), apparently due to the mechanical action induced by the volume change on thawing. Natural cleaning phenomena are not reliable, so that the mirrors may have to be washed periodically. A proposed scheme for washing is portrayed in Figure 4.[2] Certain material concerns exist at this point too. For example, a high-pH detergent can attack the glass, and residual soap film can accelerate dust buildup.[12] Precautions will be taken, therefore, by the plant operators. Mirror soiling will vary with time due to tradeoff between deposition and cleaning. Field experience is encouraging, because the heliostats in service at the Central Receiver Test Facility in Albuquerque, New Mexico, have never been washed, yet after two years show only a four percent net decrease in reflectivity (although the value does cycle between rains).

The second (reflecting) surface of the heliostats has its own set of materials-related issues. Prior to plating with reflective metal, the glass is cleaned and chemically treated to improve metal adherence. Pure silver was chosen for the pilot plant mirrors because it has an average reflectivity of 98.7 percent over the solar spectrum.[8] The actual value varies somewhat, depending upon whether the silver is deposited chemically or from the vapor.[8] Silver is subject to chemical attack (especially by water, chlorine or sulfur) and must be protected from the environment. Aluminum is much more resistant to attack, but is significantly less reflective than silver. In order to provide corrosion protection, a layer of copper traditionally is plated over the silver. The role of the copper is not clear, however; Cu is too close to Ag in the electrochemical series to provide obvious clearcut protection. Finally, a coating of "protective" paint is applied over the metal. The paint apparently is porous, however, and its brittle nature causes chipping if the mirrors must be cut to size. Improved protective coatings are being sought on a time scale commensurate with pilot plant construction.

After one year's exposure to the elements, prototype mirrors in Livermore, California have developed a visible degradation of the metallized reflecting surface. Mirror problems of this sort are not unusual; each of us is familiar with decreased reflectivity of old mirrors due to streaking or spotting of the reflective surface. Extensive instrumental analyses have been conducted in an effort to identify the cause of the degradation in the prototype heliostats. Some of the evidence is displayed in Figure 5. The general consensus at present is that the degradation problem was induced by the presence, over an extended interval, of liquid phase water which penetrated the heliostat sandwich at the silicone edge seals. Apparently, temperature changes combined with surface tension served to draw the water a considerable distance from the mirror edges and along the mirror/foam interface. Although the details of the corrosion mechanism are still uncertain, it is possible that with time, the water dissolved the copper and subsequently reacted with the silver to form AgOH.(13) An improved edge seal presently is being developed.

Materials issues for the heliostats can be summaried as follows: solarization can be favorable if attention is paid to the oxidation state and impurities. Weathering degradation exists, but the amount is probably tolerable. Corrosion has been observed on the second surfaces and related to the action of water, but the physical mechanisms are as yet uncertain. However, steps are being taken to eliminate the source of the problem. Studies to identify the most durable glasses and reflective surfaces are continuing, because this work will be of benefit to central receivers beyond the pilot plant.

Receiver Subsystem

The Barstow pilot plant receiver subsystem design gathers the concentrated solar insolation from the heliostat field in an exposed or external type receiver, as opposed to a cavity or internal type. The single-pass boiler/superheater design which will be used brings with it some new challenges for the designer and materials engineer, as we will now show. Most of these concerns center upon assuring a long service life, and do not appear to threaten the reliability or operability of the receiver.

The peak power density at the receiver will be 300 kw/m^2, with the average about 160 kw/m^2; this flux is at the maximum of single-pass-to-superheat steam boiler experience. There are 24 panels of 70 tubes each in the receiver; each tube is 0.50 inch O.D, 0.27 inch I.D. and the exposed portion is 45 feet long. The tubes are to be fabricated from Incoloy 800 and coated with 'Pyromark'®, a vitreous refractory metal oxide paint which

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develops a 95% solar absorptivity when cured. The tubes are to be GTA welded together longitudinally and continuously along the back side, using Inconel 82 filler metal. The welding is designed to improve heat transfer between adjacent tubes, to reduce shine-through losses, and to distribute the heat load should one of the tubes become plugged. The superheated steam achieves maximum conditions of 960°F and 1500 psi. The maximum metal temperature at the crown is to be below 1150°F.

The mechanical response of the receiver tubing will be determined by peak operational stress plus complications due to the daily (diurnal) thermal cycling of the receiver, departure from nucleate boiling (DNB) and the effects of time-dependent plasticity coupled with cyclic deformation. The operational stresses arise from 1) internal steam pressure, which leads to an approximately constant tensile hoop stress, and 2) differential (single-sided) heating which leads to large temperature gradients, an axial moment, and compressive axial stresses on the hot-side tube crown. The compressive axial stress is "strain controlled", because its amplitude is dictated by the front-to-back temperature differential in the tubes. Other stresses not considered here (but possibly significant) are those caused by seismic activity, particularly in Southern California, and wind loading on the tower.

Both the diurnal and DNB stresses are nonsteady with time. Cooling due to diurnal cycling plus cloud cover and maintenance shutdowns will produce about 10^5 cycles in a 30 year lifetime. The DNB stresses occur over a short length of tube, in which the transition from saturated water to saturated steam takes place. DNB flow is an inherent operating condition in once-through boiler designs. In this region of flow instability, liquid and vapor pockets alternately traverse the tube in 7 possible flow patterns[14-15], leading to rapid local temperature changes in the metal because of the difference in heat transfer coefficient between liquid and vapor. One model[14] predicts ΔT = 300°F and a frequency of 1/3 to 1/8 Hz over a 6-inch length of tube. Figure 6 shows the calculated strains arising in the tubes from combined single side heating and DNB strains.[14]

Candidate alloys for service in the pilot plant boiler/superheater included stainless steels 304L and 316L, and Incoloy 800/800H. Analysis of the low cycle fatigue problem led to the conclusion that the stainless steels probably would not last the 30-year lifetime required in the design. Based primarily upon the low cycle fatigue life, and its superior strength properties at temperature, Incoloy 800/800H was chosen as the superheater tube material.

Incoloy 800 and 800H are γ' (gamma-prime, Ni_3Ti, Al) strengthened iron-base alloys in which the precipitation of TiC and $M_{23}C_6$ carbides also may occur during elevated temperature service.[16] The nominal composition of alloy I 800 is listed in Table I, where it can be compared to alloy 800H which has been qualified for nuclear reactor use. Alloy 800 was chosen over 800H for the Pilot Plant because 800 has higher stress allowables at the temperatures of interest, as shown in Figure 7. The range of compositions of titanium and aluminum allowed by ASME specification are shown in Figure 8, along with the approximate γ' solvus at 1100°F[17]. The inner box also covers the region in which most experimental results have been obtained.

Solutionized I 800 is expected to precipitate γ' during receiver operation. Because of the creep-fatigue environment and the differential heating, the kinetics of γ' precipitation[16] are not likely to be everywhere the same within a given superheater tube. Thus the strength and ductility properties of the receiver tube panels are expected to change during the life of the pilot plant, and differences in strength and ductility from crown to backside may develop as well.

The analysis of the receiver stresses will be discussed because it requires an in-depth knowledge of material properties in order to optimize performance and lifetime. The DNB zone will be considered first. The design philosophy for the DNB zone is to uncouple the diurnal and DNB oscillations for analysis. Significant plastic strain (creep or relaxation of stress) during the hold periods does not occur in the boiling zone due to the lower temperature of the tube walls. DNB is treated as an elastic cycle. As seen in Figure 6, the small strain amplitudes allow this separation to be done with confidence. The diurnal cycle high temperature fatigue stress is considered to be the life-controlling stress variable, and in this regime, the stress allowables are high.

In the high temperature end of the boiler/superheater (beyond the 10 meter station) fatigue, cyclic hardening and stress relaxation all occur. In the analysis, the competition between cyclic hardening and stress relaxation must be quantified. Characterizition of the cyclic strain amplitude and the creep stresses is important because biasing conditions excessively toward either limiting case will diminish the receiver lifetime. For example, excessive stress relaxation (necessarily treated as creep by the designer because of data limitations*) might soften the metal and permit excessive strains in the diurnal cycle; insufficient relaxation causes a high level of cyclic stress (approximately 60 ksi) to develop and creep life could be severely limited. Thus the designer must balance these phenomena in maximizing the tube lifetime. The problem is complicated by (1) limited data on material properties under these conditions and (2) lack of an applicable design code.

Figure 9 shows an overview of the diurnal fatigue problem,[18] delineating the existing data base on creep/fatigue interactions and the liquid Metal Fast Breeder Reactor Steam Generator operating range, compared to the operating regime of the Barstow Pilot Plant. It is apparent that a large gap in information exists. Pushing the boundaries of the existing data base in the direction indicated by the arrow is an expensive procedure. Increasing the duration of tensile hold periods appears to be deleterious to I800, as shown in Figure 10,[19] but data are lacking on the effect of compressive holds. The possibility exists that greater damage may result from compressive rather than from tensile holds. The superalloys Rene 95, Inconel 100 and AF2-10A show this effect[20] because the mean stress

*Stress relaxation is a small strain phenomenon under decreasing loads while creep is a large strain phenomenon under either constant load or stress. Treatment of relaxation as creep is a necessary artifice; the small relaxation strains are unlikely to produce large amounts of creep damage.

and peak tensile stress shift towards higher values with compressive holds than with tensile holds, for the same inelastic strain range.[21] This bias develops for small inelastic strain ranges and long hold times in the superalloys, conditions which are similar to the Pilot Plant receiver tubes. Preliminary results on I 800 do not preclude the possibility that compressive hold times in this alloy also may lead to shorter lives; however, the data are too sparse as yet to permit conclusions.[22]

Efforts to correlate high cycle and low cycle fatigue test data for I 800 have led to the postulate of an endurance limit.[23] However, the correlation is sensitive to random overload or overstrain cycles ("spectrum loading"), which may cause the apparent endurance limit to disappear.[24] This result bears on the decoupling of diurnal and departure from nucleate boiling (DNB) cycling assumed for the Pilot Plant analysis. The fatigue properties of I 800 are thought to be related to γ' precipitation strengthening and its relation to mechanical response. Thus the in-service property changes must be addressed in context with the complicated stress/strain history experienced by the boiler tubes.

Because the central receiver is a boiler-pressure vessel, it is required by California law to have ASME Boiler and Pressure Vessel Code approval. An approved code or standard for construction of solar-fired boilers does not as yet exist, however. The Barstow receiver will have an ASME section I stamp. Section I of the Code explicitly considers only hoop (pressure) stresses, which are related to short-term (overload) and long-term (creep) failures through application of arbitrary ('experience') factors. Because all of the ASME code sections depend to some extent upon operating experience and accumulations of data, their application to solar boilers is more properly viewed at this time as "standards of construction" rather than as Regulatory Codes. Optimization of solar-powered boiler codes would include assessment of creep-fatigue interactions, tensile and compressive hold time effects, spectrum loading effects, damage accumulation, and in-service property changes. A preliminary solar-powered boiler code has been developed by Foster-Wheeler corporation at the request of Sandia Laboratories Livermore[25], and the ASME has convened a working group to explore solar codes and data needs. Because of the evolutionary nature of regulatory codes, these efforts are only a beginning.

Several internal and external environment issues also confront the designers of the pilot plant receiver. These issues are, as are all of those discussed here, lifetime or durability issues. The primary environmental issue is corrosion fatigue of internal surfaces. In once-thru systems, continuous full-flow demineralization is required to hold impurities in the parts-per-billion (ppb) range. Higher levels cannot be tolerated because there is no steam drum to permit periodic "blowdowns". The large feedwater inventory of a solar boiler accentuates the problem. The concern is that corrosion-cracking of the containment materials may be accelerated by the inherently cyclic nature of the solar boiler, in contrast to conventional systems. The likelihood of scale formation is enhanced in the DNB zone, due to the impurity - concentrating effect of continuous boiling in a short length of tubing. Furthermore, diurnal cycling may induce oxide scale breakaway, presenting problems of tube plugging, turbine erosion, and erosion of the tube walls. Corrosion fatigue in the dryout zone is of concern because of the increased local concentration of impurities in combination with nonsteady stress and possible welding effects, such as residual stresses and sensitization. Programs are underway at several laboratories to address the significance of these potential interactions.

Few studies have been performed on the behavior of austenitic alloys in steam evaporators. However, I 800 apparently is difficult to sensitize, as can be seen in Figure 11. No carbide precipitation ($M_{23}C_6$, or $Cr_{23}C_6$) is visible in the heat affected zone of these welds. The mid-life microstructure, as determined by time, temperature, and strain history, would provide a useful estimate of the stress corrosion cracking (corrosion fatigue) resistance of the alloy; however, this microstructure is not yet known. Historically, metallurgical control of stress corrosion cracking in alloy 800 has focused on the Ti:C ratio and its relation to intergranular corrosion(26). Large Ti:C ratios, 8:1 or more, are required to minimize intergranular failure. However, absolute levels of Ti and C may also be important.(27) Recent work has indicated that the open-circuit cracking potential may change as a function of Ti:C ratio and that conflicting results in the literature may reflect that fact.(28) This possibility has not been conclusively demonstrated.

The external environment of the desert is a sufficiently unknown quantity that assessing the hazard to the receiver is difficult. Although alkali halides, organics and condensed water are present near ground level, the atmospheric components at receiver height have not been identified. Sampling programs are underway to determine the components of the environment. Prior to this analysis, assessing the external hazard is speculative.

Storage Subsystem

Energy storage of some type will probably be essential for solar central receivers, in order to permit power generation during cloudy periods, to extend operating hours, and to "buffer" the steam system during cloud transients. The storage subsystem for the Pilot Plant is designed to contain sufficient sensible heat to permit generation of $7MW_e$ for 4 hours without sunlight. The system employs a dual medium thermocline concept, using oil, rock and sand. The rock and sand reduce the oil volume and provide some heat storage. "Thermocline" refers to the use of one tank to contain both hot and cold liquids, with a sharp stable interface developing between the two. The interface moves up or down as hot liquid is added above, and cool withdrawn below, or vice-versa. In this way the tank size and thermal losses are reduced. In the Pilot Plant, Caloria HT43®, a petroleum fraction, has been proposed for use with local granite rocks and sand. The temperature cycle is from 300°C (575°F) to 218°C (425°F) with a volume change of 9%, and a nitrogen cover gas to prevent oxidation of the oil. The secondary steam

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generation shown in Figure 12 produces steam at 275°C and 2.7 MPa (525°F and 385 psia).

Most of the materials concerns in the storage subsystem involve the stability and compatibility of the oil/rock and containment materials. Although apparently cost effective compared to other storage concepts, the use of an organic fluid in long-term applications at higher temperatures than these appears unlikely because of the limitation imposed on allowable temperatures.

The first metals concern for the storage subsystem has to do with structural performance. The tank is to be fabricated from A537 steel. When heat is added, the tank will expand, and if the rock settles, the tank will be prevented from contracting upon subsequent cooling. Following this scenario, cyclic operation could produce incremental growth, or rachetting. Although computer analysis suggests that this phenomenon may occur,[29] experiment does not evidence such behavior[2]; therefore, the issue must remain as a possible, if unlikely, problem. The rock may be susceptible to long-term fragmentation induced by thermal stresses, and this could affect the rachetting behavior. In summary, designers and analysts believe that rachetting will be small and self-limiting.

Four separate concerns have been identified under the topic of "chemical" effects in the storage subsystem: initial thermochemical properties of the oil, long-term thermal stability of the oil, oil-rock interaction, and corrosion of the storage vessel. We will describe briefly each of these in turn.

In systems which store energy as sensible heat, the storage capacity depends upon the specific heat of the oil and the rock. Supporting studies[30] for the pilot plant program have revealed that specific heats of as-received oils of the same label may vary by as much as 11 percent. The variations correlate with differences in average molecular weights and homogeneity of the samples. However, the impact on system cost is less than 1 percent for oil/rock systems and less than 2 percent for an all-oil system.

Long-term breakdown of the organic fluid may change thermophysical properties and affect storage performance. The scenario is displayed in Figure 13. Potential instabilities could include vaporization, thermal cracking, and oxidation, leading to changes in viscosity, deposits in the tank, and impaired storage capacity. Chemical interactions between the oil and the rock could produce further problems. The possibility exists for the generation of organic acids from the reaction of oil oxidation products with rock-entrapped water. Alternatively, mineral acids may be formed from water and sulfates, chlorides, or flouride interactions. Either contaminant in the oil will induce corrosion of the steel storage vessel or heat exchangers; one can even hypothesize a scenario for hydrogen attack of the vessel. Specific types of chemical attack would depend upon rock type and oil composition. Chemical variations of natural rock and the possibility of thermal attrition of the rock make this variable difficult to predict. However, the rock is to be quarried near the pilot plant site, and samples will be analyzed with regard to water content, soluble chlorides, fluorides, or sulfates. The corrosion mechanisms must be known before processes for control (or even the need for control) can be certain. Representative values for fluid losses in an operating thermal storage system, and their economic impact, have been quantified.[30,31]

Electrical Power Generation Subsystem

The electrical power generation subsystem is to be assembled from primarily commercial components common to power generating plants and in industry. Therefore, the majority of the materials concerns will be those that are known to the industry. For the pilot plant, anticipated steam turbine material problems include thermal fatigue or stress corrosion of the blades, and erosion of or deposits on the blades. Copper, for example, is an historic offender. Copper dissolved in the feedwater likely would transfer with the steam and deposit on the turbine blades or plate on the boiler tubes. For this reason the condenser for the pilot plant will employ titanium alloy tubes instead of the alternative cupronickel alloy.

Most of the issues listed in the preceeding paragraph are of magnified concern in the solar pilot plant because of the once-through boiler concept. We mentioned earlier that conventional boiler/superheater steam generators incorporate an intermediate steam drum where solids can be removed by "blow-down". In the pilot plant, feedwater purity will be maintained by full-flow demineralization (condensate polishing), leading to the steady-state water chemistry specifications listed in Table II.[5, 15] Condensate polishers afford high flow rates and although their primary function is to remove dissolved matter, they also act as mechanical filters for suspended corrosion products. Ammonia and hydrazine will be added for pH and oxygen control; the pH is chosen to protect the carbon steel feedwater train. Iron and copper will be controlled to limit the amount of corrosion and depositable material from the preboiler system. The conductivity value is specified to guard against corrosion in the demineralization columns, and the hydrazine limit is imposed to avoid "over-feeding" with consequent release of hydrogen. Sodium and chlorides will be controlled in order to limit stress corrosion cracking, and silica will be controlled to avoid harmful deposits on the turbine.[15]

Closure

As described in the introduction, the primary purposes of the pilot plant are to establish the technical feasibility of a central receiver-type solar thermal plant, and to attain sufficient development, production, and operating data to help evaluate the potential economic operation of commercial plants of similar design. In addition to these primary goals, the plant is also expected to provide operational data that can be used to determine system stability and safety characteristics, develop both utility and commercial acceptance of solar thermal central receiver systems, and enhance public acceptance and familiarity with solar central receiver types of systems.

All of the subsystem components described herein for the pilot plant were selected in order to provide high probability for pilot plant success (including cost performance). As with all new technologies, from a materials standpoint extrapolations from an existing database are necessary in order to design for the thirty-year life requirement. Predictions of long-term material performance must be made from an information base which is limited in size, or from short-term accelerated laboratory experiments. The materials and systems studies from which this report was compiled indicate that the pilot plant development program is, as was intended, leading to discovery of the critical concerns and encounters with the important new variables associated with establishment of a new technology. No materials problems have arisen which are of a nature to delay the pilot plant; rather, the issues have to do with economics and longevity, and studies are underway to resolve these issues for the pilot plant and future systems as well.

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TABLE I

LIMITING COMPOSITIONS OF ALLOYS 800 AND 800H

	800	800H
Nickel	30-35	30-35
Chromium	19-23	19-23
Iron	remainder	remainder
Carbon	0.1 max	0.06-0.10
Manganese	1.50 max	1.50 max
Sulfur	0.030 max	0.015 max
Silicon	1.0 max	1.0 max
Copper	0.75 max	0.75 max
Aluminum	0.15 - 0.60	0.15 - 0.60
Titanium	0.15 - 0.60	0.15 - 0.60
Grain size	---	ASTM 5 (large)

TABLE II

FEEDWATER SPECIFICATIONS

Total Solids	50 PPB
Dissolved Oxygen	7 PPB
Silica	20 PPB
Iron	10 PPB
Copper	2 PPB
pH @ 25°C	9.3 to 9.6
Hydrazine	3 PPB
Conductivity (cation) at 25°C	0.3 micro mho/cm
Sodium	2 PPB
Chloride	2 PPB

ILLUSTRATIONS

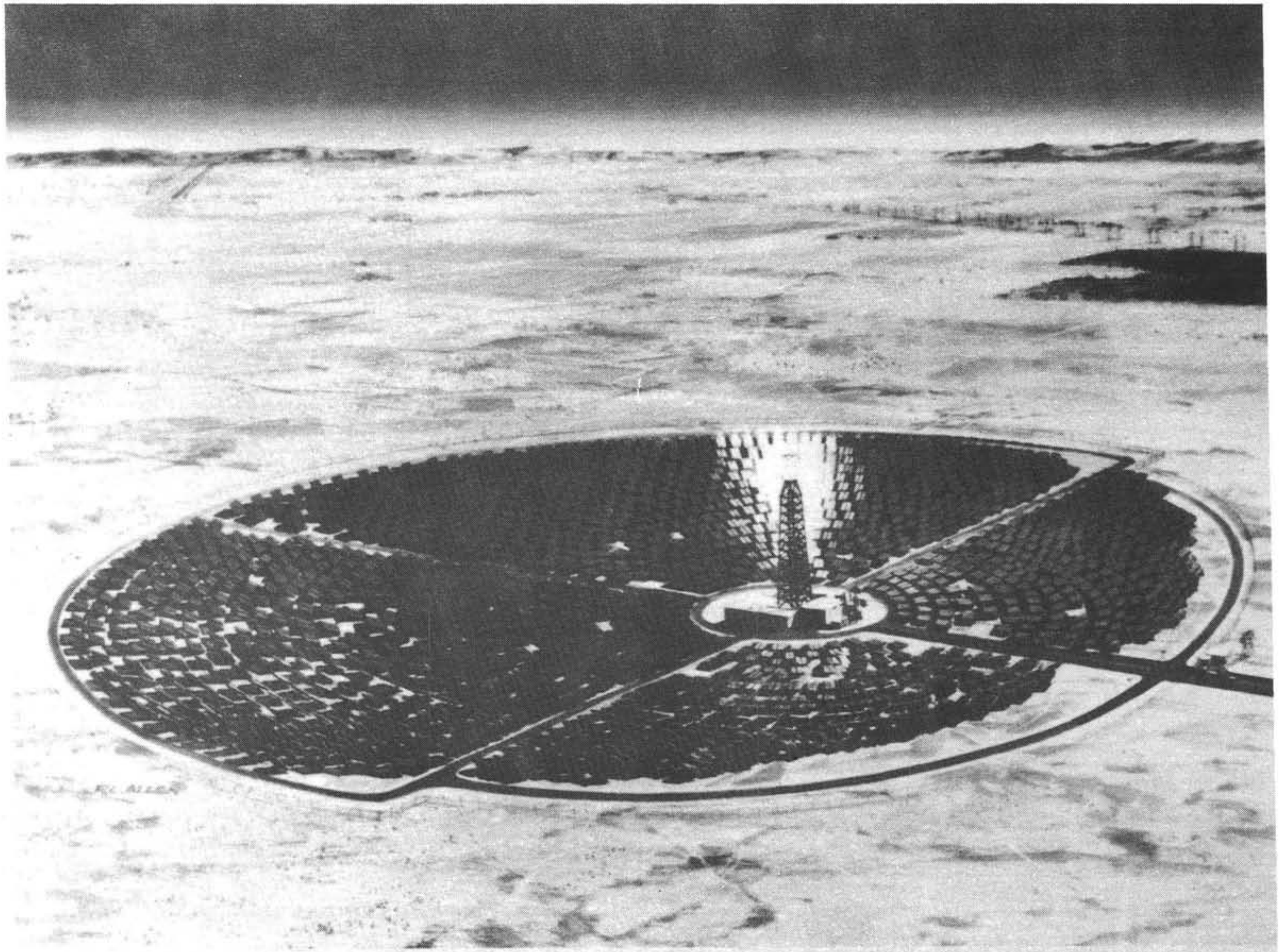

Figure 1. Artists' rendition of 10 MW_e solar thermal electric pilot plant.

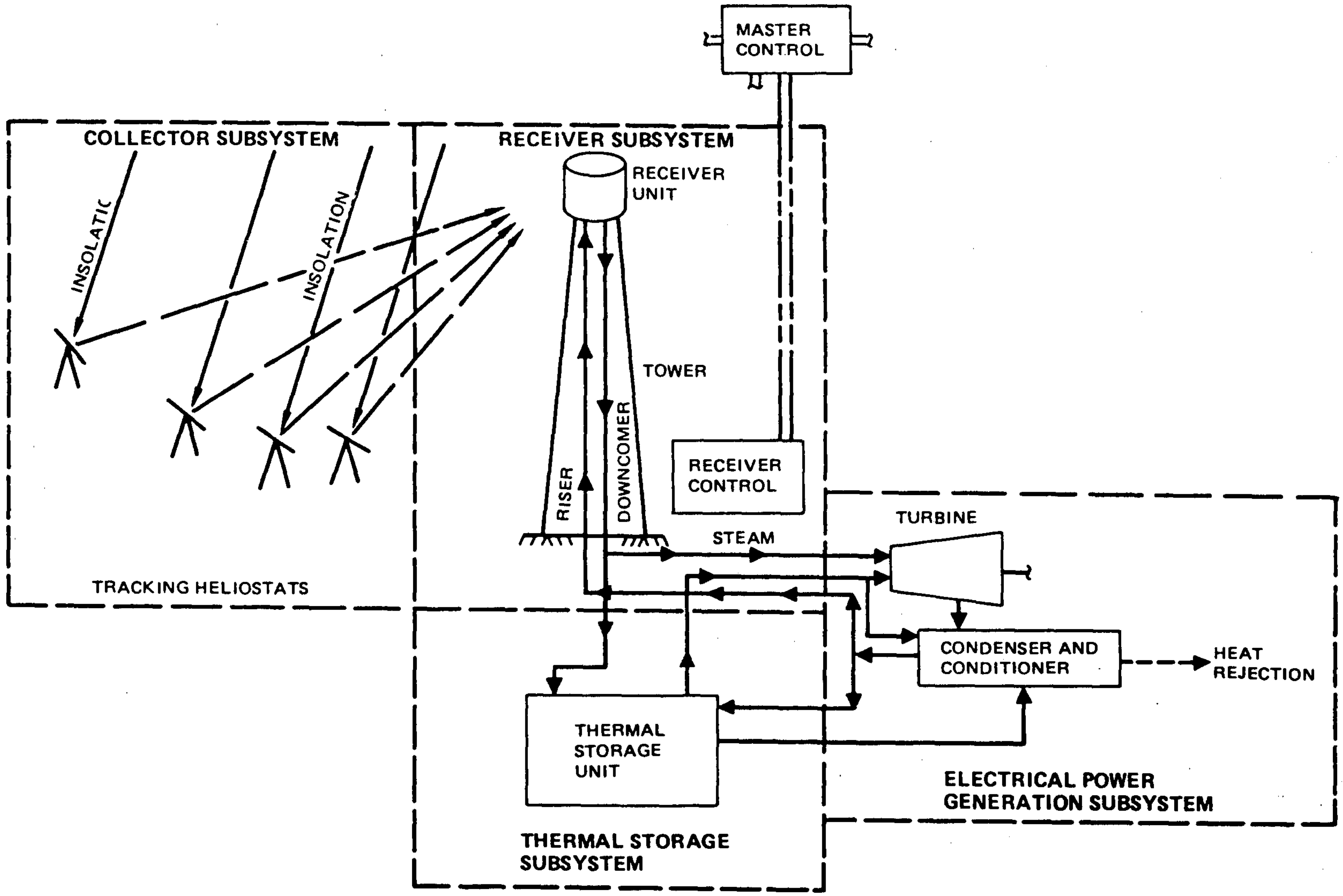

Figure 2. Subsystem description of the pilot plant. (2)

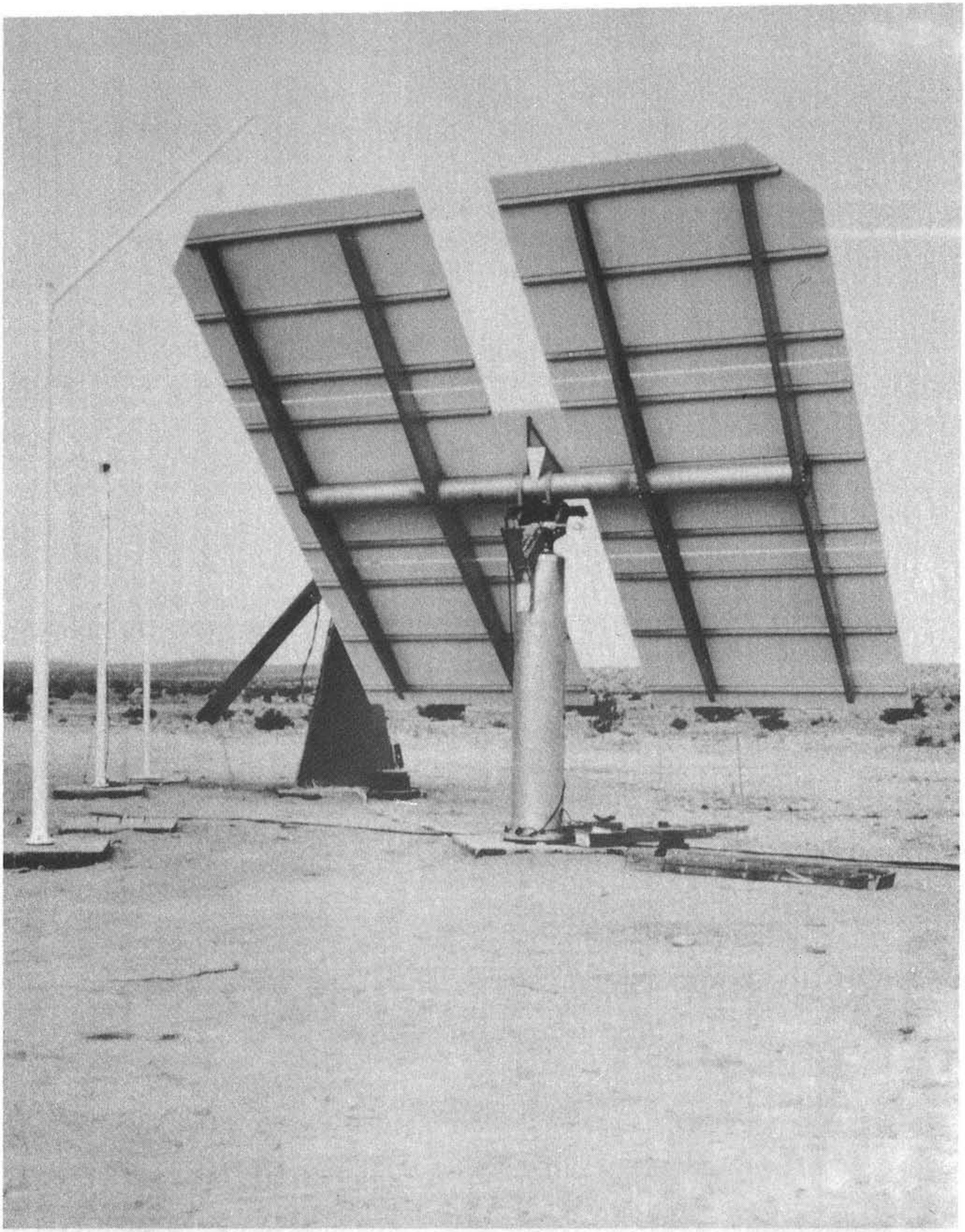

Figure 3. Prototype heliostat.[2]

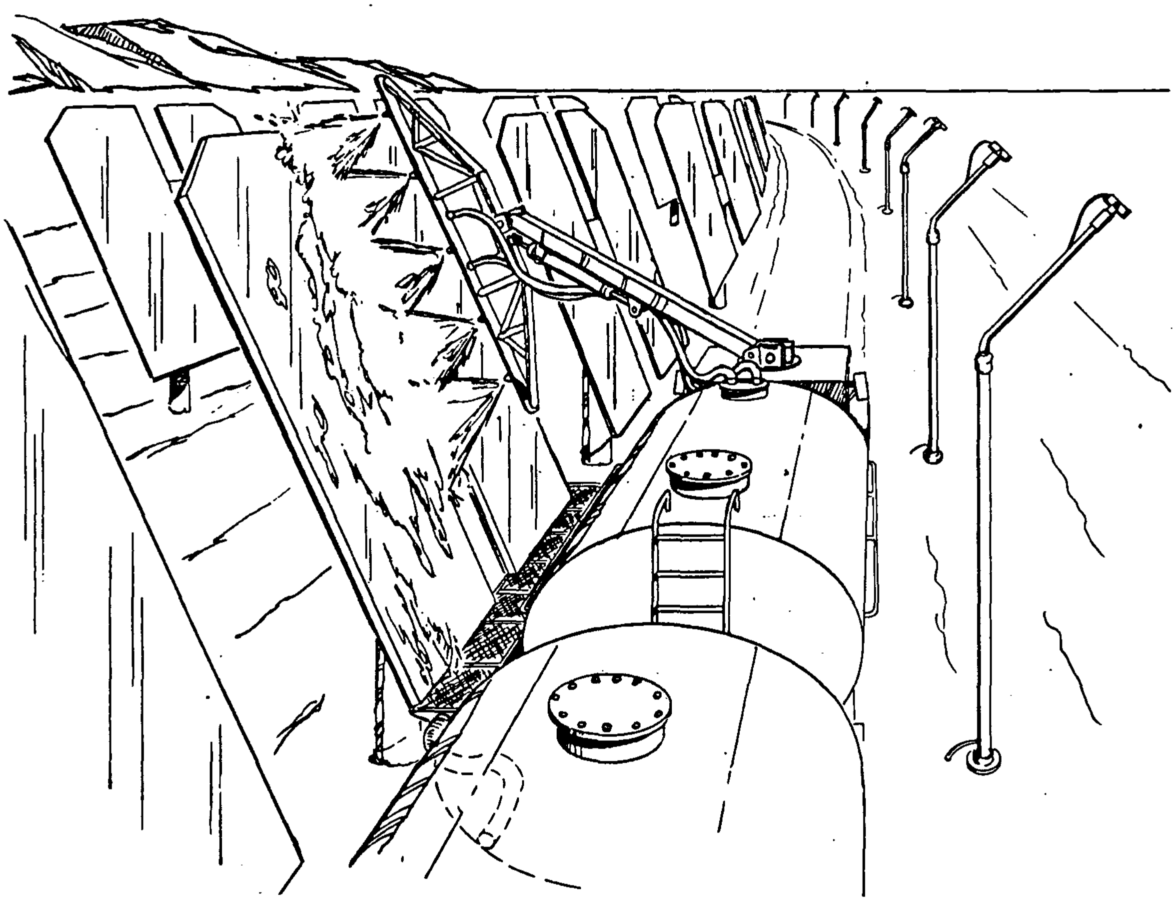

Figure 4. Artists concpetion of heliostat washing procedure.[2] The sun-sensors shown are not part of the present scheme.

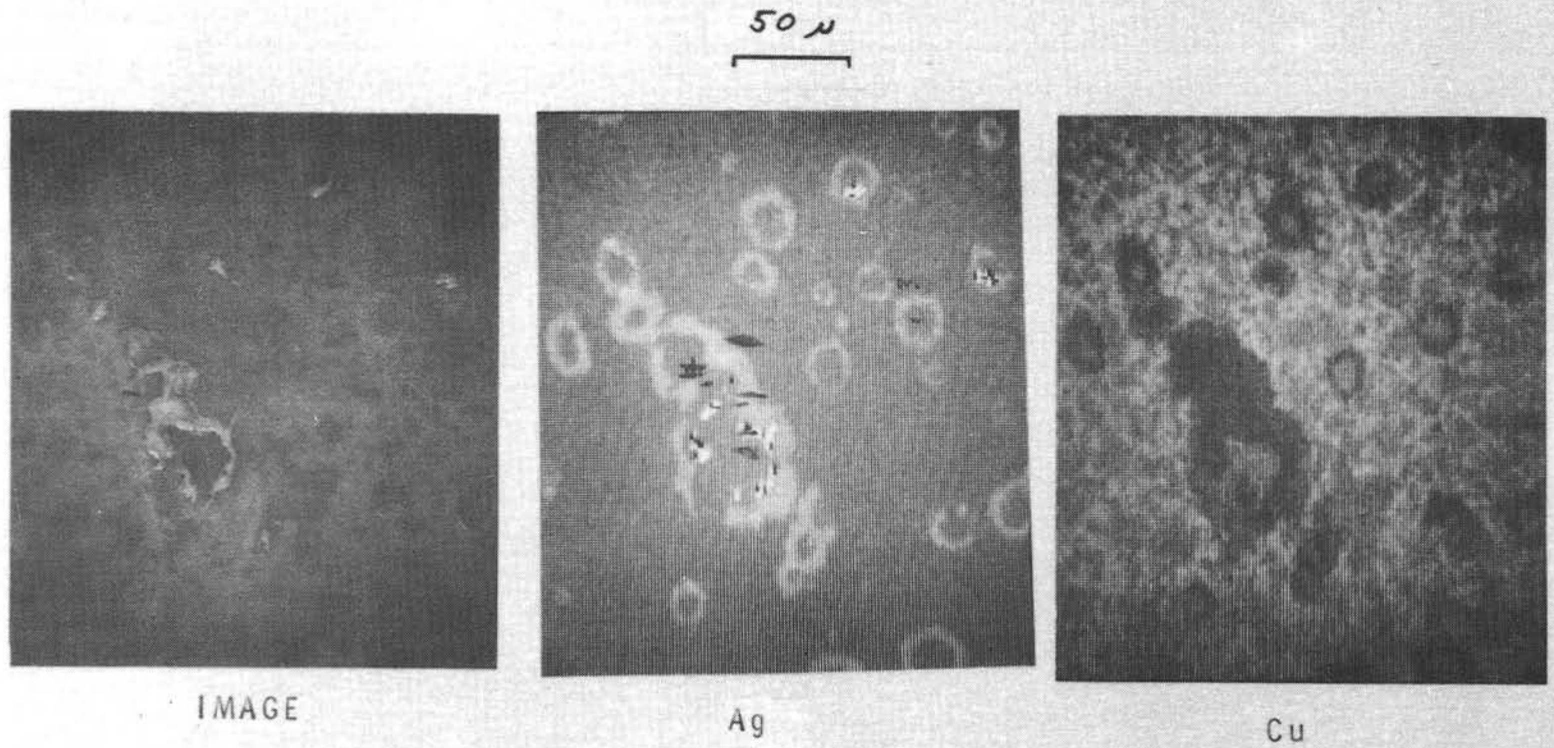

Figure 5. Scanning electron microscope and scanning auger microprobe analyses of localized degredation on mirror reflective surface.

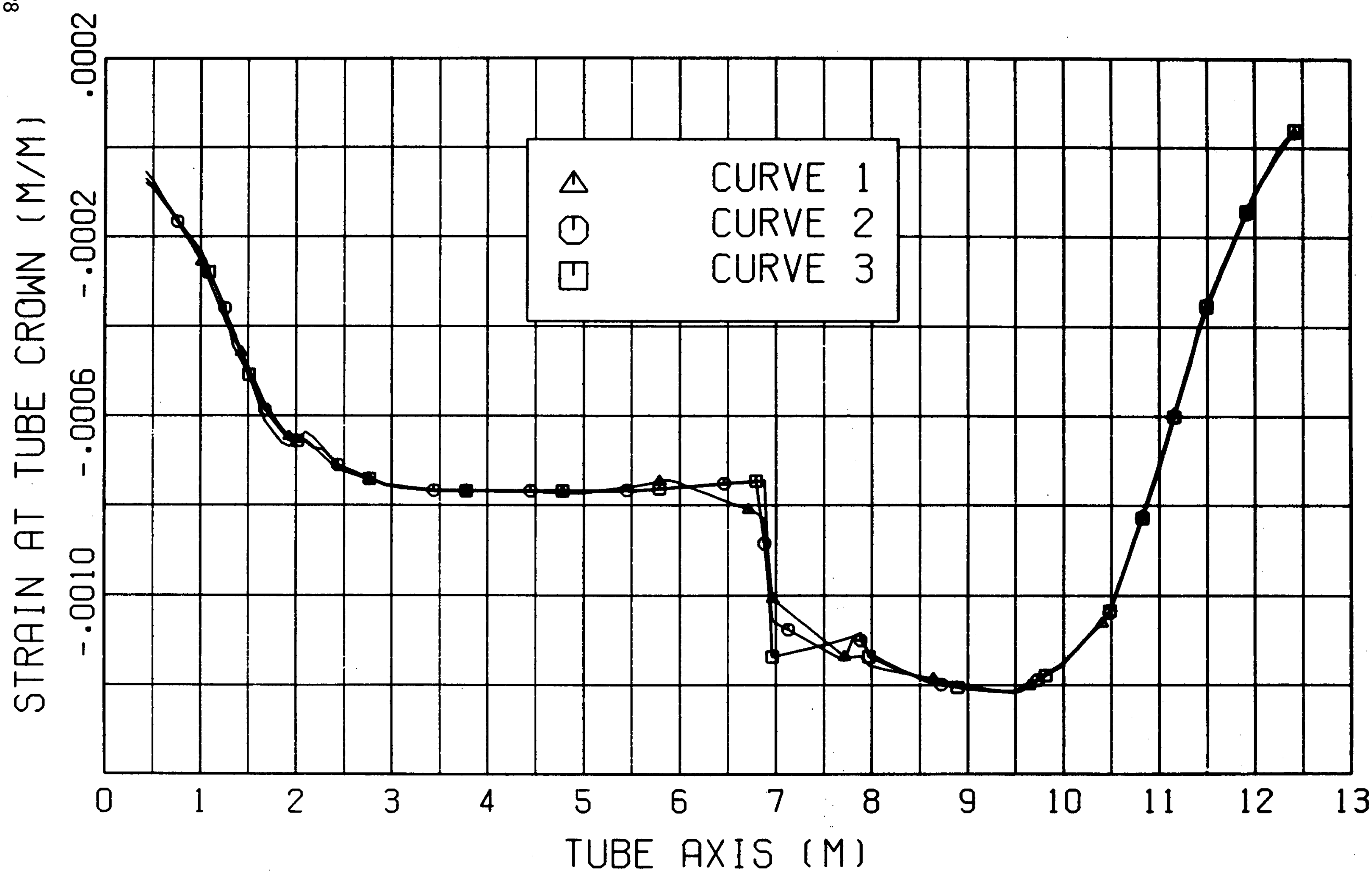

Figure 6. Calculated strains in superheater tubes.

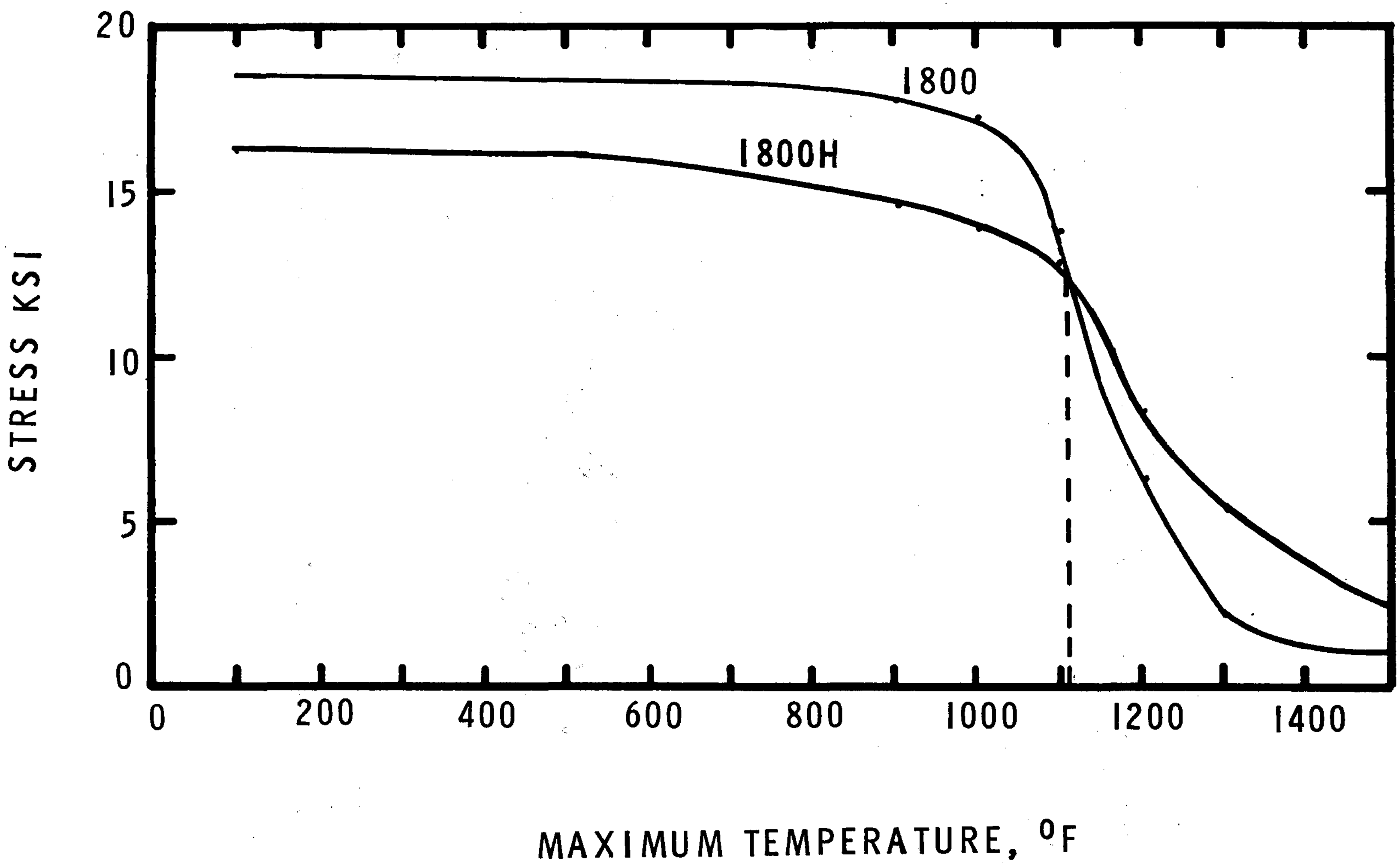

Figure 7. Stress allowable as function of temperature for alloy 800 according to Section VIII of the ASME Boiler and Pressure Vessel Code.

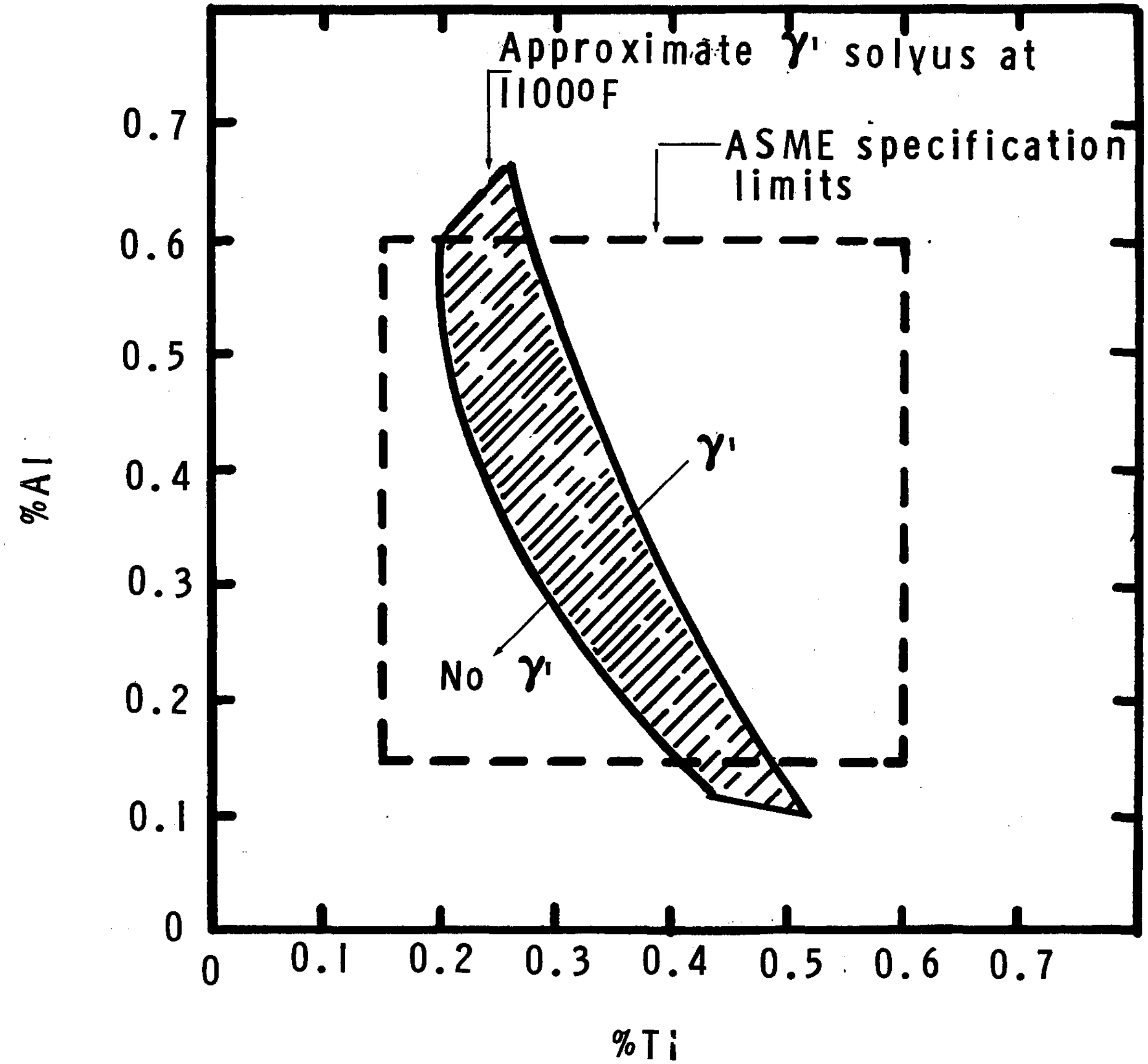

Figure 8. Nominal range of Al + Ti) compositions and the γ' solvus in I800 at 1100°F.

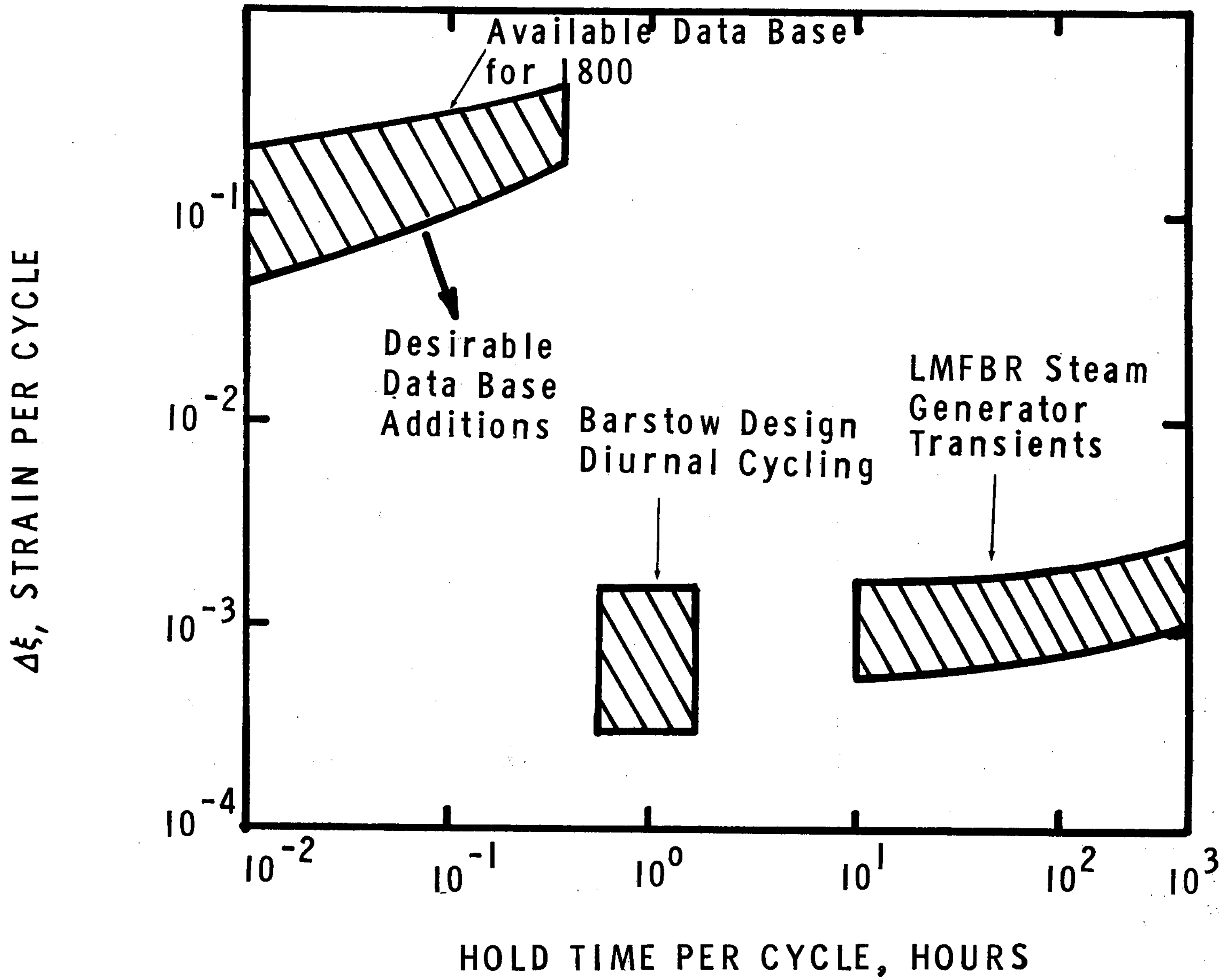

Figure 9. Overview of diurnal fatigue problem in Solar Central Receiver Pilot Plant.

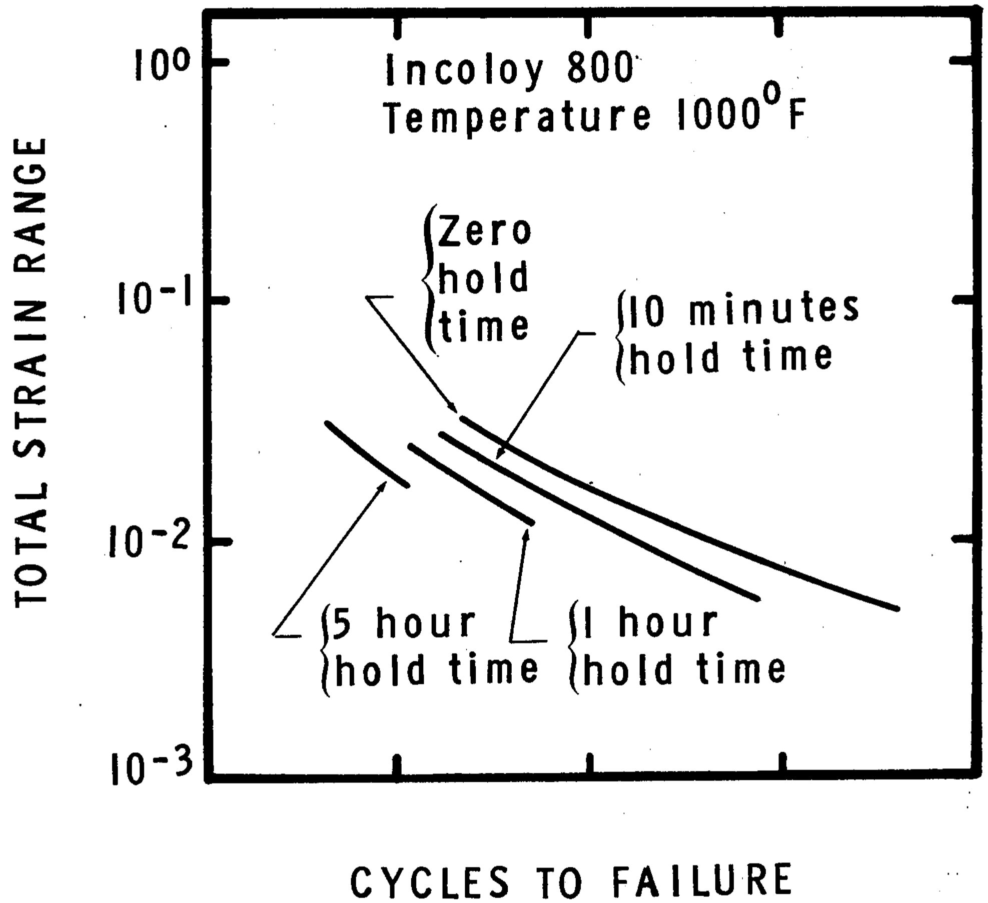

Figure 10. Tensile hold time effects in fatigue, after Majumdar. (19)

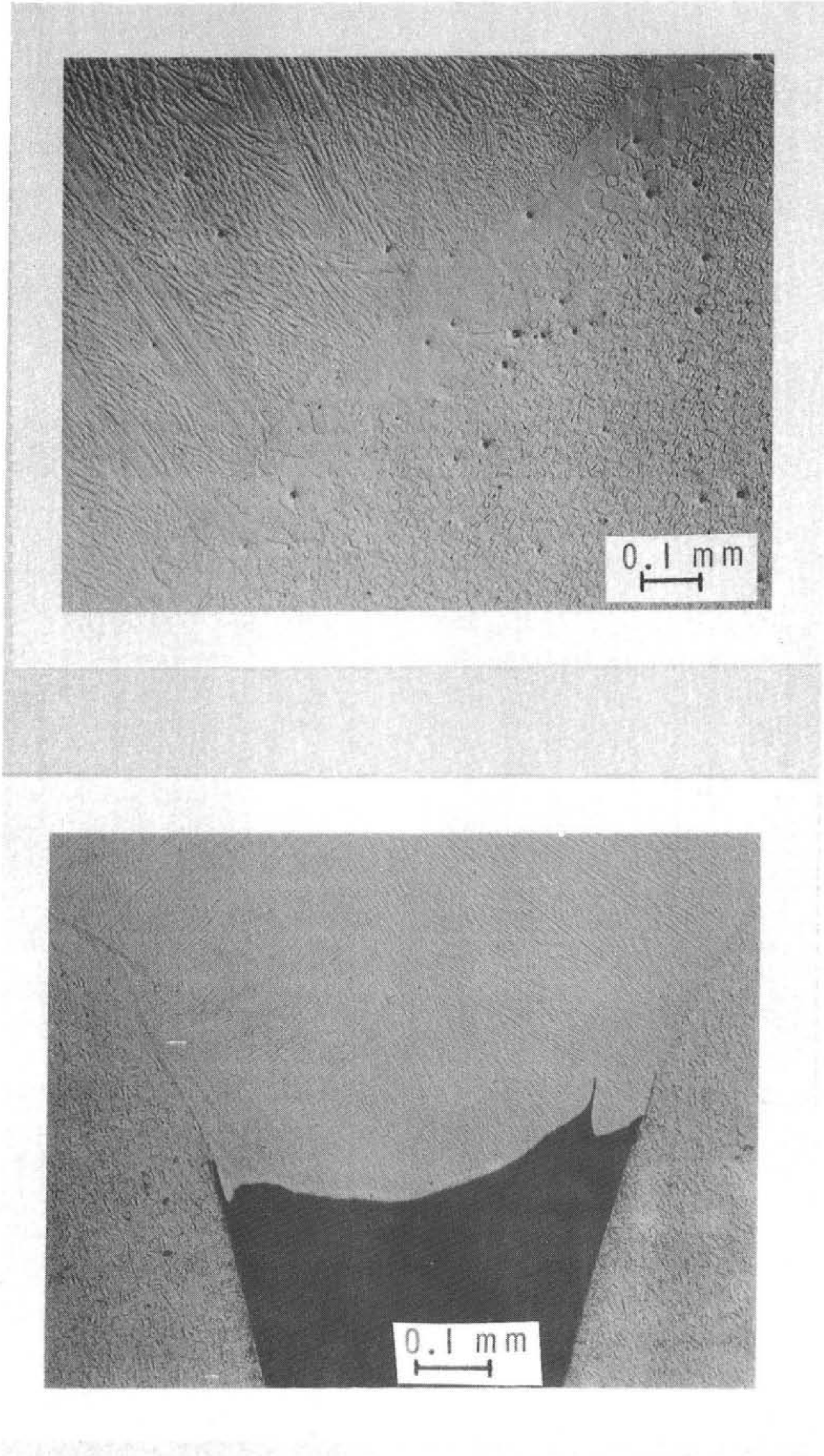

Figure 11. Optical micrograph of welded tube joints.

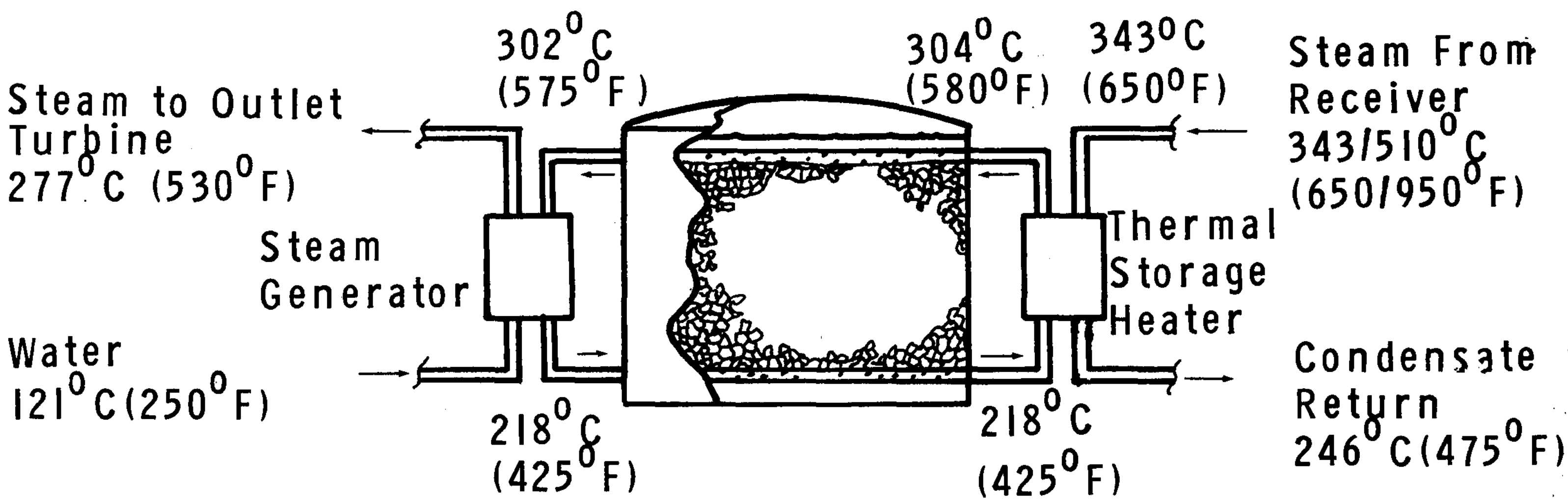

Figure 12. Storage system and secondary steam generator - schematic.

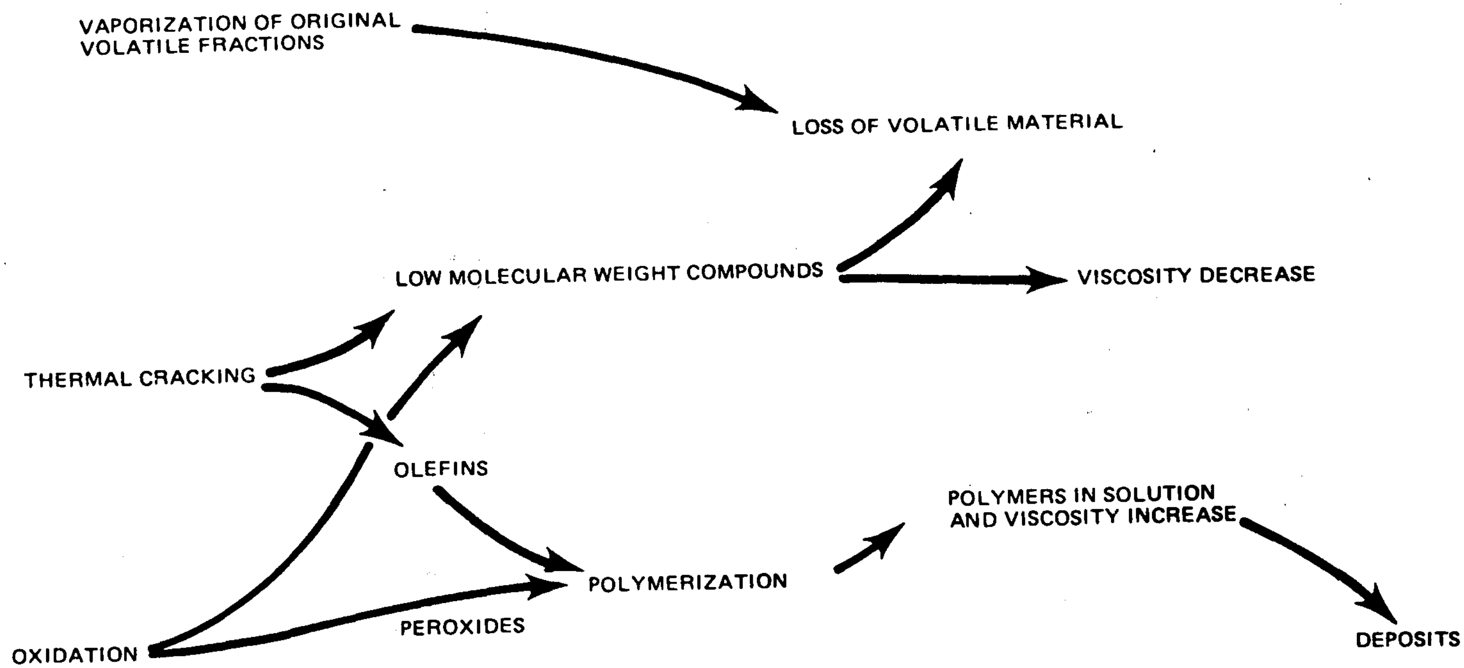

Figure 13. Fluid maintenance considerations for storage of hot oil.[2]

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