NOTES
Observations started February 1940.
T: Air temperatures in degrees Fahrenheit.
For isothermal curves see Denver Office.
Drawing No. 245-0-1194.

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO-BIG THOMPSON PROJECT - COLO.

GRAND LAKE

TEMPERATURES IN GRAND LAKE
DEPTH - TEMPERATURE CURVES FOR 1940

DRAWN: E.O.S
SUBMITTED: E.O.S
TRACED: E.O.S
CHECKED: E.O.S
APPROVED: E.O.S

DENVER, COLORADO - JUN 30, 1941
245-0-1193
<table>
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**NOTES**
Water temperature observations started February 1940.
Only controlling temperatures shown to depth of 100 feet.
For depth-temperature curves see Denver Office Dwg.
No. 245-D-193.

**UNITED STATES**
**DEPARTMENT OF THE INTERIOR**
**BUREAU OF RECLAMATION**
COLORADO-BIG THOMPSON PROJECT - COLO

**GRAND LAKE**
**TEMPERATURES IN GRAND LAKE**
**ISOThermal CURVES FOR 1940**

**DRAWN:** E.S.P.
**TRACED:** E.C.E.
**CHECKED:** M.C.C.
**APPROVED:**

DENVER, COLORADO - JAN. 3, 1944
245-D-1194
Notes:
Observations started February 1941.
Temperature in degrees Fahrenheit.
No observations made from Feb 28 to May 31 due to unsafe ice conditions.
For isothermal curves see Denver Office Drawing No. 245-0-1616.

United States Department of the Interior
Bureau of Reclamation
Colorado-Big Thompson Project - Colo

Grand Lake Temperatures in Grand Lake Depth - Temperature Curves for 1941

Drawn: C.E.W. Submitted: J.T. Richardson
Checked: J.T.R. Approved: N.W. Walker
Denver, Colorado - March 3, 1942

245-0-1615
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**NOTES**

Water temperature observations started February 1940.

Only controlling temperatures shown to depth of 100 feet.

No observations were made from Feb 28 to May 31 due to unsafe ice conditions.

--- Indicates probable isothermal curves for period from Feb 28 to May 31.

For depth-temperature curves see Denver Office.

Drawing No. 245-D-1685.
NOTES

Water temperature observations started in
February (1940)
T = Air temperature in degrees Fahrenheit
No observations were made from March 30 to
May 30 due to unsafe ice conditions.
For isothermal curves see Denver Office
Drawing No. 245-D-088
Water temperature measurements discontinued
with November record.
NOTES
Water temperature observations started in February 1940.
Only controlling temperatures shown to depth of 100 feet.
No observations were made from March 30 to May 30 due to unsafe ice conditions.
- - - - Indicates probable isothermal curves for period from March 30 to May 30.
For depth-temperature curves see Denver Office.
Drawing No. 245-0-1942
Water temperature measurements discontinued with November record.

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO-BIG THOMPSON PROJECT
GRAND LAKE
TEMPERATURES IN GRAND LAKE
Isothermal Curves for 1942

DENVER, COLORADO - AUGUST 13, 1943
245-D-1983
Colorado Big Thompson Tunnels and Canals
May 7, 1952

Robert E. Glover
Pole hill tunnel outlet

Pole hill canal
Pole Hill

Penstock site

Pole Hill afterbay structures.
Pole Hill bench flume.

Rattlesnake tunnel, dam and reservoir.
Bald Mountain tunnel outlet

Flatiron penstock site.
Flatiron penstock site.

Flatiron power house site.
Flatiron power house.
Big Thompson diversion structure

Sluice gate construction.
Diversion gate at tunnel №1.

Outlet of tunnel №1.
Horsetooth Feeder canal at tunnel No. 1

Horsetooth Feeder canal at Big Thompson.
Structures at Big Thompson Siphon.

Structures at Big Thompson Siphon.
Gates at Big Thompson Siphon Structure.
Horseshoe Feeder Canal - This photograph shows the first water coming through Tunnel No. 1 after the ice jam at the outlet portal was loosened. All the water in the Big Thompson River was diverted into the tunnel to break loose the slush ice formed in the canal.
12-11-51 Bureau of Reclamation photo by R. E. Holdsworth

Horseshoe Feeder Canal - Water backed up in the flume at the outlet portal of tunnel is shown. Additional head was required to break ice jam in the canal below.
12-11-51 Bureau of Reclamation photo by R. E. Holdsworth

Horseshoe Feeder Canal - Slush ice is shown at the radial gate of the Big Thompson Siphon.
12-11-51 Bureau of Reclamation photo by R. E. Holdsworth

Horseshoe Feeder Canal - This photograph shows a crew of men attempting to clear the ice in the gate to the Big Thompson wastewater. Note the height of the slush ice in the opening of the Big Thompson Siphon at the left.
12-11-51 Bureau of Reclamation photo by R. E. Holdsworth

Horseshoe Feeder Canal - The pile of slush ice was photographed at the bifurcation structure east of Tunnel No. 1. The photograph was taken before any water was sent through the tunnel in an attempt to break the ice. Water standing in the bottom is ice which has been melted by the sun.
12-11-51 Bureau of Reclamation photo by R. E. Holdsworth

Horseshoe Feeder Canal - Photograph showing the depth of slush ice in Horseshoe Feeder Canal. Note size of man standing on the bank.
12-11-51 Bureau of Reclamation photo by R. E. Holdsworth

Horseshoe Feeder Canal - Photograph taken looking down the wastewater into the Big Thompson River, showing discharge. The entire flow of the Big Thompson River at the Diversion Structure was turned into the Horseshoe Feeder Canal and then through the wastewater to break and remove the ice.
12-11-51 Bureau of Reclamation photo by R. E. Holdsworth

Horseshoe Feeder Canal - Method of melting the ice on the gates to the Big Thompson wastewater is shown. First the men used a pick to break the ice, and then a woodburner melted the ice behind the gates.
12-11-51 Bureau of Reclamation photo by R. E. Holdsworth
Horsetooth Feeder Canal - This photograph was taken from the north side of the Big Thompson Siphon looking downstream, showing one of the methods used to break ice in the bottom of the canal. A walking plow with the blade cut down, towed by a truck, is being used. The rope shown on the left side of the picture is operated by a man in order to keep the plow in an upright position.
12-11-31 Bureau of Reclamation photo by R. E. Holdsworth

Horsetooth Feeder Canal - This photograph was taken on the north side of the Big Thompson Siphon, showing the plow in operation.
12-11-31 Bureau of Reclamation photo by R. E. Holdsworth

Horsetooth Feeder Canal - Photograph showing the water leaving Tunnel No. 1 after it had broken the ice jam below.
12-11-31 Bureau of Reclamation photo by R. E. Holdsworth

Horsetooth Feeder Canal - Photograph showing ice in the flume at the east portal of Tunnel No. 1 before any water was sent through.
12-11-31 Bureau of Reclamation photo by R. E. Holdsworth

Horsetooth Feeder Canal - Photograph showing the amount of slush ice in the Horsetooth Feeder Canal before any water was sent through.
12-11-31 Bureau of Reclamation photo by R. E. Holdsworth

Horsetooth Feeder Canal - The slush ice at the outlet portal of Tunnel No. 1 is shown, before any water was sent through.
12-11-31 Bureau of Reclamation photo by R. E. Holdsworth

Horsetooth Feeder Canal - The water is shown breaking through the slush ice in the canal. Some scooped under, but most of it flowed over the top.
12-11-31 Bureau of Reclamation photo by R. E. Holdsworth

Horsetooth Feeder Canal - The slush ice in Horsetooth Feeder Canal is shown in this photograph taken from Station 54+00 looking downstream, before any water was sent through.
12-11-31 Bureau of Reclamation photo by R. E. Holdsworth
To: Mr. R. E. Clover

From: Mr. C. H. Zanger

Subject: Strain measurements, stresses, and concrete lining for Prospect Mountain Tunnel—Colorado-Big Thompson Project.

1. Introduction

On about April 1, 1947, it was decided to place strain gages, in the form of rosettes, on the rock walls of Prospect Mountain Tunnel. The purpose of this experimental work was to determine the magnitude of stresses on the tunnel walls and to use this information in arriving at a decision as to whether or not steel reinforcement is necessary in the proposed concrete tunnel lining.

The strain measurements were obtained by O. J. Olsen and are contained in a report to Mr. E. Clover dated April 23, 1947. A summary of this data is included here in Table II. Stresses determined from the strain measurements indicate a compressive stress at all gage points. This is a favorable stress condition which will compensate for the tensile stresses produced later by internal water pressure and temperature changes.

Strain rosettes were located, in general, at the crown, at the horizontal diameter, and 45° below the horizontal diameter on the tunnel wall at Stations 943+30, 953+27, 957+39, 967+30 and 979+40.

Gage directions of the individual rosettes were measured counter-clockwise as viewed from inside of the tunnel, from the 0° axis which was taken downstream.

Stresses have also been estimated in the region of the tunnel, by analytical methods, for the conditions of rock overburden, internal water pressure, and temperature effects. A computation has also been made to determine the magnitude of a crack opening due to the water pressure if no lateral stresses existed in the rock.

The diameter of the lined tunnel was taken as 12.5 feet and of the unlined tunnel as 14.5 feet. The length of the tunnel was taken as 5,650 feet. A profile of the mountain with the grade line of the tunnel is shown in Figure 1.

All stresses in this report are given in pounds per square inch. The following paragraphs, figures and tables give the results of this study.
2. **Comments**

It is understood that the maximum emergency water surface at Marys Lake may be at elevation 3045. This would increase the effective head by 10 feet which in turn would increase the tensile stresses due to the internal pressure by 4.3 pounds per square inch at the wall of the tunnel. This small valve is considered unimportant in this study.

3. **Basic Data and Notations**

The following basic data was used in the various computations:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Inside diameter of lined tunnel,</td>
<td>12.5 feet</td>
</tr>
<tr>
<td>Approx. diameter of unlined tunnel,</td>
<td>11.5 feet</td>
</tr>
<tr>
<td>Length of tunnel,</td>
<td>5,650 feet</td>
</tr>
<tr>
<td>Water surface elevation, Marys Lake,</td>
<td>8,035.0</td>
</tr>
<tr>
<td>Water surface in surge tank,</td>
<td>8,057.1</td>
</tr>
<tr>
<td>Elevation of centerline of tunnel at Station 907.45</td>
<td>7,963.25</td>
</tr>
<tr>
<td>Elevation of centerline of tunnel at Station 933.400</td>
<td>7,988.61</td>
</tr>
<tr>
<td>E, modulus of elasticity of steel,</td>
<td>$30 \times 10^6$ lb per sq.in.</td>
</tr>
<tr>
<td>Er, modulus of elasticity of rock,</td>
<td>$5.4 \times 10^6$ lb per sq.in.</td>
</tr>
<tr>
<td>Ec, modulus of elasticity of concrete,</td>
<td>$2 \times 10^6$ lb per sq.in.</td>
</tr>
<tr>
<td>( \mu ), poisson's ratio for rock,</td>
<td>0.14</td>
</tr>
<tr>
<td>( g ), density of rock,</td>
<td>162.5 lb per cu.ft.</td>
</tr>
<tr>
<td>( \alpha ), coefficient of expansion of rock,</td>
<td>$4.5 \times 10^6$ per degree F</td>
</tr>
<tr>
<td>Temperature of water,</td>
<td>32°F</td>
</tr>
<tr>
<td>Mean annual temperature of rock, at surface of mountain</td>
<td>52°F</td>
</tr>
<tr>
<td>At temperature differential,</td>
<td>20°F</td>
</tr>
<tr>
<td>Allowable stress in steel reinforcement,</td>
<td>$24,000$ lb per sq.in.</td>
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</tbody>
</table>

Table II gives the station, tunnel location, and gage direction in degrees, and the strain rosette readings used in the computations (data obtained from O. J. Olsen).

Other notation used:

- a represents internal radius of lined tunnel
- au radius of unlined tunnel
- b radius from center of tunnel to outside of mountain
- c width of rectangular foundation considered in computing amount of crack opening
- d length of rectangular foundation considered in computing amount of crack opening
- E modulus of elasticity
natural logarithm
internal pressure in tunnel
radius to any point
elongation of tunnel radius
coefficient of expansion
temperature differential
mean deflection parallel to axis
strain, tensile is positive
maximum principal stress
minimum principal stress
stress longitudinal to tunnel axis
stress transverse to tunnel axis
maximum shear
angle between axis of tunnel and positive when measured counterclockwise
Poisson's ratio
the normal stress which acts in the direction of the radius
the normal stress which acts in the direction of the tangent
the shear stress along the radial and tangential planes
stress in rock in neighborhood of the tunnel
an angle in degrees measured clockwise or counterclockwise from the vertical

T,
thickness of tunnel lining

4. Technical Details

The stresses around the tunnel as given in this report were determined as follows:

a. The stresses indicated by the strain rosette measurements were computed using the following equations:

\[ \sigma_1 = \frac{E \varepsilon}{2(1 + \mu)} \left[ \frac{1}{2} \cdot \frac{1}{1 - \mu} \left( \varepsilon_0 \neq \varepsilon_{45^\circ} \neq \varepsilon_{90^\circ} \neq \varepsilon_{135^\circ} \right) \right. 
\]

\[ - \sqrt{\left( \varepsilon_0 - \varepsilon_{90^\circ} \right)^2 + \left( \varepsilon_{45^\circ} - \varepsilon_{135^\circ} \right)^2} \]

\[ \sigma_2 = \frac{E \varepsilon}{2(1 + \mu)} \left[ \frac{1}{2} \cdot \frac{1}{1 - \mu} \left( \varepsilon_0 \neq \varepsilon_{45^\circ} \neq \varepsilon_{90^\circ} \neq \varepsilon_{135^\circ} \right) \right. 
\]

\[ + \sqrt{\left( \varepsilon_0 - \varepsilon_{90^\circ} \right)^2 + \left( \varepsilon_{45^\circ} - \varepsilon_{135^\circ} \right)^2} \]
\[ \tan 2\theta = -\frac{\varepsilon_{450} - \varepsilon_{1350}}{\varepsilon_{00} - \varepsilon_{900}} \]
\[ \varepsilon_{00} \neq \varepsilon_{900} = \varepsilon_{450} \neq \varepsilon_{1350} \]

2. For the condition of four gages, located at 0°, 60°, 90°, and 120° (see Section 7, References, h):

\[ \sigma_1 = \frac{E}{2} \left[ \frac{\varepsilon_{00} + \varepsilon_{900} - \frac{1}{2} \varepsilon_{450}}{1 - \mu} \right] \left[ \varepsilon_{00} - \varepsilon_{900} \right] \left[ \frac{\varepsilon_{00} - \varepsilon_{900}}{2} \right] \left[ \frac{\varepsilon_{600} - \varepsilon_{1200}}{2} \right] \]
\[ \sigma_2 = \frac{E}{2} \left[ \frac{\varepsilon_{00} + \varepsilon_{900} - \frac{1}{2} \varepsilon_{450}}{1 - \mu} \right] \left[ \varepsilon_{00} - \varepsilon_{900} \right] \left[ \frac{\varepsilon_{00} - \varepsilon_{900}}{2} \right] \left[ \frac{\varepsilon_{600} - \varepsilon_{1200}}{2} \right] \]
\[ \tan 2\theta = \frac{2}{\sqrt{3}} \left[ \frac{\varepsilon_{600} - \varepsilon_{1200}}{\varepsilon_{00} - \varepsilon_{900}} \right] \]
\[ \frac{1}{2} \varepsilon_{00} \neq \frac{1}{2} \varepsilon_{900} = \varepsilon_{600} \neq \varepsilon_{1200} \]

The results of these computations are shown by Tables 1, 2, 3, 4, and 5, and figures 2, 3, and 4.

b. The stresses in the neighborhood of the tunnel (when tunnel is nonexistent) due to the weight of the rock were computed using the following equations (see Section 7, References, j):

\[ \sigma_x = E \left[ \frac{-2 \alpha \beta y}{(\alpha + \beta)^2} \right] \left[ \frac{\alpha \beta}{(\alpha + \beta)^2} \right] \]
\[ \sigma_y = E \left[ \frac{2 \alpha \beta y}{(\alpha + \beta)^2} \right] \left[ \frac{\alpha (\beta - \alpha)}{(\alpha + \beta)^2} \right] \]
\[ \tau_{xy} = E \left[ \frac{\alpha (\beta - \alpha) + 2 \alpha}{(\alpha + \beta)^2} \right] \frac{\alpha \beta}{(\alpha + \beta)^2} \]

\[ \sigma_z, \text{ Transverse stress indeterminate} \]

The figure below shows use of symbols:

\[ y = 1010 \text{ feet} \]
\[ \alpha = 0.780 \]
\[ \beta = 0.644 \]
c. The stresses due to the weight of the rock (when the tunnel actually exists) computed using Equations (14), Page 11, T.M. 223 (see Section 7, References f):

The equations used are given below:

\[ \sigma_r = \frac{s}{2} \left[ 1 - \frac{4a^2}{r^2} \left( 1 - \frac{4a^2}{r^2} \right) \cos 2\psi \right] \]

\[ \sigma_t = \frac{s}{2} \left[ 1 + \frac{a^2}{r^2} - \left( 1 + \frac{3a^4}{r^4} \right) \cos 2\psi \right] \]

\[ \tau_{rt} = \frac{s}{2} \left[ -1 + \frac{2a^2}{r^2} - \frac{3a^4}{r^4} \sin 2\psi \right] \]

\[ \sigma_x \text{ omitted} \]

Results of this computation are shown by Table 10.

d. The stresses due to internal water pressure in the tunnel were computed using Equations (6), Page 7, T.M. 223 (see Section 7, References, f):

The equations used are given below:

\[ \sigma_r = -p \frac{\alpha^2}{r^2} \]

\[ \sigma_t = +p \frac{\alpha^2}{r^2} \]

\[ \sigma_x = 0 \]

Results of this computation are shown on Table 6.

e. The maximum thermal stress occurs at the initial admission of water. At this instant, radial stress is zero, and longitudinal and tangential stresses are equal at the tunnel surface, as given by the following development:

\[ \varepsilon_x = \frac{\sigma_x}{E_R} - \frac{\mu \sigma_y}{E_R} + \Delta \tau \alpha = 0 \]

\[ \varepsilon_y = -\frac{E_R \sigma_x}{E_R} + \frac{\sigma_y}{E_R} + \Delta \tau \alpha = 0 \]

\[ \sigma_x - \mu \sigma_y = -E_R \Delta \tau \alpha \]

\[ -\mu \sigma_x + \sigma_y = -E_R \Delta \tau \alpha \]
Solving these equations gives: for a 20°F temperature drop

\[
\sigma_x = \sigma_y = -\frac{E_t \Delta t \alpha}{1 - \mu} = -\frac{(5.4 \times 10^6)(20)(4.5 \times 10^{-6})}{1 - 0.14} = -565 \text{ lb/in}^2
\]

After operating long enough so a steady state of heat flow may be assumed, the temperature distribution will be logarithmic, and the following relations for stress apply (see Section 7, References, b):

\[
\sigma_x = \frac{E_t \alpha \Delta t b}{2(1-\mu) \log_2 \frac{b}{r} + 1}
\]

\[
\sigma_t = \frac{E_t \alpha \Delta t}{2(1-\mu) \log_2 \frac{b}{r}} \left[ 1 - \log_2 \frac{b}{r} - \frac{g^2}{b^2 - a^2} \left( 1 + \frac{b^2}{r^2} \right) \log_2 \frac{b}{r} \right]
\]

\[
\sigma_r = \frac{E_t \alpha \Delta t}{2(1-\mu) \log_2 b} \left[ -\log_2 \frac{b}{r} - \frac{g^2}{b^2 - a^2} \left( 1 - \frac{b^2}{r^2} \right) \log_2 \frac{b}{r} \right]
\]

The results of this computation are shown by Figure 5.

f. The change in radius of the tunnel due to internal water pressure was computed using Equation (9), Page 8, T.M. 223 (see Section 7, References f.):

\[
U = \frac{\Delta u}{E_t} \left( 1 + \mu \right)
\]

Assuming the pressure in the tunnel is 40 lbs/in²:

\[
U = \frac{(87)(40)}{5.4 \times 10^6} = 0.000735 \text{ inches}
\]

g. The determination of width of crack opening under internal water pressure was based on the following equation (see Section 7, References g.):

\[
\Delta Z = \left( 1 - \mu \right) \frac{p}{E_t} \left( c \left( 1 + \frac{2 \log(2a)}{\pi} \right) \right)
\]

if the following values are assigned,

\[
\mu = 0.14
\]

\[
p = 40.4 \text{ lbs/in}^2
\]

Lateral pressure - none.
\[ E_r = 5.4 \times 10^6 \text{ lbs/in}^2 \]
\[ c = 14.5 \text{ ft} = 174 \text{ inches (Case I)} \]  
\[ 1.024 \text{ feet} = 1682.36 \text{ inches (Case II)} \]  
\[ d = 2650 \text{ ft} = 67,800 \text{ inches} \]

Note: In Case II it is assumed that the water pressure has extended the initial crack to the elevation of zero pressure.

Then,

\[
\text{Case I, } \Delta \bar{z} \text{ mean} = \left[ 1 - (0.14)^2 \right] \frac{30.4 (174)}{5.4 \times 10^3} \left[ 1 + 2 \log \left( \frac{2 \times 174}{100} \right) \right] 
\]

Width of crack opening = \( 2 \Delta \bar{z} \text{ mean} \)

= 0.0057 inches

\[
\text{Case II, } \Delta \bar{z} \text{ mean} = \left[ 1 - (0.14)^2 \right] \frac{30.4 (1682.36)}{5.4 \times 10^3} \left[ 1 + 2 \log \left( \frac{2 \times 1682.36}{100} \right) \right] 
\]

= 0.026691 inches

Width of crack opening = 0.058 inches

5. References

a. Theory of Elasticity by Timoshenko, Page 77.

b. Strength of Materials by Timoshenko, Page 554, Part II.


d. U. S. Bureau of Reclamation Specifications No. 1167, Excavation and Concrete Lining Mesa Horn and Prospect Mountain Tunnels.

e. Paper by Frederic Vogt, Oslo, Norway, 1925, "About the Calculations of Foundation Deformations," Translated by F. Bier, October 1937.


g. Determination of principal stresses from strains on four intersecting gage lines 45° apart, by Mr. R. Osgood, Journal of Research of the National Bureau of Standards, Volume 13, July–December 1935.
h. A Heliographic Solution to the Strain Rosette Equations
   by Thomas A. Hewson—Proceedings of the Society for
   Experimental Stress Analysis, Volume IV 1946.

i. Photoelasticity by Frcott, Volume I, John Wiley and Sons.

j. U.S.B.R. T.M. 547; Heliographic Determination of Boundary
   Stresses in Gravity Dams, by J. E. Bechlese, W. T. Moody,

6. Personnel

Personnel that assisted in the preparation of this report were

[Signature]
### TABLE I
Station 943+80

<table>
<thead>
<tr>
<th>Location</th>
<th>$\varepsilon_0 \cdot \varepsilon_{90}$</th>
<th>$\varepsilon_{45} \cdot \varepsilon_{135}$</th>
<th>$\sigma_i$</th>
<th>$\sigma_2$</th>
<th>$T_{\text{MAX}}$</th>
<th>$\theta$</th>
<th>$\sigma_x$</th>
<th>$\sigma_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>1335</td>
<td>786</td>
<td>-4700</td>
<td>-2000</td>
<td>-1350</td>
<td>$1\frac{1}{3}^\circ$</td>
<td>-2000</td>
<td>-4700</td>
</tr>
<tr>
<td>R. Side</td>
<td>710</td>
<td>799</td>
<td>-3100</td>
<td>-1650</td>
<td>-725</td>
<td>$13^\circ$</td>
<td>-1750</td>
<td>-3000</td>
</tr>
<tr>
<td>L. Side</td>
<td>836</td>
<td>817</td>
<td>-3200</td>
<td>-2000</td>
<td>-600</td>
<td>$28^\circ$</td>
<td>-2250</td>
<td>-2950</td>
</tr>
<tr>
<td>R. Bottom</td>
<td>952</td>
<td>752</td>
<td>-3450</td>
<td>-1900</td>
<td>-800</td>
<td>$36^\circ$</td>
<td>-2450</td>
<td>-2900</td>
</tr>
<tr>
<td>L. Bottom</td>
<td>971</td>
<td>744</td>
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<td>-2200</td>
<td>-500</td>
<td>$-25^\circ$</td>
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### TABLE II
Station 953+97

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<th>Location</th>
<th>$\frac{1}{2}\varepsilon_0 \cdot \frac{1}{2}\varepsilon_{90}$</th>
<th>$\varepsilon_{60} \cdot \varepsilon_{120}$</th>
<th>$\sigma_i$</th>
<th>$\sigma_2$</th>
<th>$T_{\text{MAX}}$</th>
<th>$\theta$</th>
<th>$\sigma_x$</th>
<th>$\sigma_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>446</td>
<td>412</td>
<td>-2000</td>
<td>-250</td>
<td>-900</td>
<td>$31\frac{1}{2}^\circ$</td>
<td>-750</td>
<td>-1500</td>
</tr>
<tr>
<td>R. Side</td>
<td>1435</td>
<td>1474</td>
<td>-5900</td>
<td>-2300</td>
<td>-1800</td>
<td>$35\frac{1}{2}^\circ$</td>
<td>-3500</td>
<td>-4700</td>
</tr>
<tr>
<td>L. Side</td>
<td>1105</td>
<td>1124</td>
<td>-3950</td>
<td>-2500</td>
<td>-750</td>
<td>$-31^\circ$</td>
<td>-2900</td>
<td>-3550</td>
</tr>
<tr>
<td>R. Bottom</td>
<td>1447</td>
<td>1430</td>
<td>-5050</td>
<td>-2300</td>
<td>-1400</td>
<td>$6^\circ$</td>
<td>-2350</td>
<td>-5000</td>
</tr>
<tr>
<td>L. Bottom</td>
<td>1457</td>
<td>1109</td>
<td>-4850</td>
<td>-3750</td>
<td>-550</td>
<td>$-22^\circ$</td>
<td>-3900</td>
<td>-4700</td>
</tr>
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</table>
### TABLE III
#### Station 957+39

<table>
<thead>
<tr>
<th>Location</th>
<th>$\frac{1}{2}E_{0^<em>} + \frac{1}{2}E_{60^</em>}$</th>
<th>$E_{60^<em>} - E_{120^</em>}$</th>
<th>$\sigma_1$</th>
<th>$\sigma_2$</th>
<th>$\tau_{\text{MAX}}$</th>
<th>$\theta$</th>
<th>$\sigma_x$</th>
<th>$\sigma_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>2654</td>
<td>4054</td>
<td>-9150</td>
<td>-4500</td>
<td>-2350</td>
<td>7°</td>
<td>-4550</td>
<td>-9100</td>
</tr>
<tr>
<td>L. Side</td>
<td>$E_{90^<em>} + E_{90^</em>}$</td>
<td>$E_{45^<em>} - E_{135^</em>}$</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1041</td>
<td>1044</td>
<td>-4900</td>
<td>-1650</td>
<td>-1625</td>
<td>-10°</td>
<td>-1750</td>
<td>-4800</td>
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### TABLE IV
#### Station 967+30

<table>
<thead>
<tr>
<th>Location</th>
<th>$E_{90^<em>} + E_{90^</em>}$</th>
<th>$E_{45^<em>} - E_{135^</em>}$</th>
<th>$\sigma_1$</th>
<th>$\sigma_2$</th>
<th>$\tau_{\text{MAX}}$</th>
<th>$\theta$</th>
<th>$\sigma_x$</th>
<th>$\sigma_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>1485</td>
<td>1633</td>
<td>-5300</td>
<td>-4450</td>
<td>-425</td>
<td>6°</td>
<td>-4450</td>
<td>-5300</td>
</tr>
<tr>
<td>L. Side</td>
<td>739</td>
<td>857</td>
<td>-3850</td>
<td>-1150</td>
<td>-1350</td>
<td>28°</td>
<td>-1750</td>
<td>-3250</td>
</tr>
<tr>
<td>R. Bottom</td>
<td>684</td>
<td>1060</td>
<td>-3900</td>
<td>-1550</td>
<td>-1175</td>
<td>-13°</td>
<td>-1650</td>
<td>-3800</td>
</tr>
<tr>
<td>L. Bottom</td>
<td>Insufficient data - Core fractured while drilling along a rock seam.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### TABLE V
Station 979+60

<table>
<thead>
<tr>
<th>Location</th>
<th>$\varepsilon_{0} + \varepsilon_{90}$</th>
<th>$\varepsilon_{45} + \varepsilon_{135}$</th>
<th>$\sigma_{1}$</th>
<th>$\sigma_{2}$</th>
<th>$\sigma_{MAX}$</th>
<th>$\theta$</th>
<th>$\sigma_{X}$</th>
<th>$\sigma_{Y}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>1327</td>
<td>1043</td>
<td>-6000</td>
<td>-1450</td>
<td>-2275</td>
<td>0$^\circ$</td>
<td>-1450</td>
<td>-6000</td>
</tr>
<tr>
<td>R. Side</td>
<td>436</td>
<td>327</td>
<td>-1700</td>
<td>-700</td>
<td>-500</td>
<td>4$^{1/2}$°</td>
<td>-700</td>
<td>-1700</td>
</tr>
<tr>
<td>L. Side</td>
<td>3155</td>
<td>2793</td>
<td>-1100</td>
<td>-7650</td>
<td>-1800</td>
<td>-15$^{1/2}$°</td>
<td>-7850</td>
<td>-10850</td>
</tr>
<tr>
<td>R. Bottom</td>
<td>544</td>
<td>347</td>
<td>-1900</td>
<td>-900</td>
<td>-500</td>
<td>-28$^{1/2}$°</td>
<td>-1150</td>
<td>-1650</td>
</tr>
<tr>
<td>L. Bottom</td>
<td>251</td>
<td>245</td>
<td>-1100</td>
<td>-450</td>
<td>-350</td>
<td>-19$^{1/2}$°</td>
<td>-500</td>
<td>-1050</td>
</tr>
</tbody>
</table>

In the above TABLES I through V:

(-) indicates compression.

$\sigma_{X}$ is stress longitudinal to tunnel.

$\sigma_{Y}$ is stress transverse to tunnel.

$+\theta$ measured counterclockwise from 0$^\circ$ axis when viewed from inside of tunnel.

$\varepsilon$ readings are in microinches per inch.

All stresses are given in Pounds Per Square Inch.
### Table 6

Transverse Stresses at Face of Tunnel

<table>
<thead>
<tr>
<th>Station</th>
<th>Location of Strain Rosette</th>
<th>Stress due to</th>
<th>Sum of Stresses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Strain Measure-</td>
<td>Water Load</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ment</td>
<td></td>
</tr>
<tr>
<td>943+80</td>
<td>Top</td>
<td>-4700</td>
<td>+24</td>
</tr>
<tr>
<td></td>
<td>R. Side</td>
<td>-3000</td>
<td>+24</td>
</tr>
<tr>
<td></td>
<td>L. Side</td>
<td>-2950</td>
<td>+24</td>
</tr>
<tr>
<td></td>
<td>R. Bottom</td>
<td>-2900</td>
<td>+24</td>
</tr>
<tr>
<td></td>
<td>L. Bottom</td>
<td>-3000</td>
<td>+24</td>
</tr>
<tr>
<td>953+97</td>
<td>Top</td>
<td>-1500</td>
<td>+29</td>
</tr>
<tr>
<td></td>
<td>R. Side</td>
<td>-4700</td>
<td>+29</td>
</tr>
<tr>
<td></td>
<td>L. Side</td>
<td>-3550</td>
<td>+29</td>
</tr>
<tr>
<td></td>
<td>R. Bottom</td>
<td>-5000</td>
<td>+29</td>
</tr>
<tr>
<td></td>
<td>L. Bottom</td>
<td>-4700</td>
<td>+29</td>
</tr>
<tr>
<td>957+39</td>
<td>Top</td>
<td>-9100</td>
<td>+30</td>
</tr>
<tr>
<td></td>
<td>L. Side</td>
<td>-4800</td>
<td>+30</td>
</tr>
<tr>
<td>967+30</td>
<td>Top</td>
<td>-5300</td>
<td>+33</td>
</tr>
<tr>
<td></td>
<td>L. Side</td>
<td>-3250</td>
<td>+33</td>
</tr>
<tr>
<td></td>
<td>R. Bottom</td>
<td>-3800</td>
<td>+33</td>
</tr>
<tr>
<td>979+60</td>
<td>Top</td>
<td>-6000</td>
<td>+38</td>
</tr>
<tr>
<td></td>
<td>R. Side</td>
<td>-1700</td>
<td>+38</td>
</tr>
<tr>
<td></td>
<td>L. Side</td>
<td>-1050</td>
<td>+38</td>
</tr>
<tr>
<td></td>
<td>R. Bottom</td>
<td>-1650</td>
<td>+38</td>
</tr>
<tr>
<td></td>
<td>L. Bottom</td>
<td>-1050</td>
<td>+38</td>
</tr>
</tbody>
</table>

In the above table:

- All stresses are given in Pounds per Square Inch.
- (-) indicates compression.
- (+) indicates tension.
### Table 7

Longitudinal Stresses at Face of Tunnel.

<table>
<thead>
<tr>
<th>Station</th>
<th>Location of Strain Rosette</th>
<th>Stress due to Strain Measurement</th>
<th>Water Load</th>
<th>Temp.</th>
<th>Sum of Stresses</th>
</tr>
</thead>
<tbody>
<tr>
<td>943+80</td>
<td>Top</td>
<td>-2000</td>
<td>0</td>
<td>+565</td>
<td>-1435</td>
</tr>
<tr>
<td></td>
<td>R. Side</td>
<td>-1750</td>
<td>0</td>
<td>+565</td>
<td>-1185</td>
</tr>
<tr>
<td></td>
<td>L. Side</td>
<td>-2250</td>
<td>0</td>
<td>+565</td>
<td>-1685</td>
</tr>
<tr>
<td></td>
<td>R. Bottom</td>
<td>-2450</td>
<td>0</td>
<td>+565</td>
<td>-1685</td>
</tr>
<tr>
<td></td>
<td>L. Bottom</td>
<td>-2400</td>
<td>0</td>
<td>+565</td>
<td>-1835</td>
</tr>
<tr>
<td>953+97</td>
<td>Top</td>
<td>-750</td>
<td>0</td>
<td>+565</td>
<td>-185</td>
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<tr>
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<td>R. Side</td>
<td>-3500</td>
<td>0</td>
<td>+565</td>
<td>-2935</td>
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<tr>
<td></td>
<td>L. Side</td>
<td>-2900</td>
<td>0</td>
<td>+565</td>
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<tr>
<td></td>
<td>R. Bottom</td>
<td>-2350</td>
<td>0</td>
<td>+565</td>
<td>-1785</td>
</tr>
<tr>
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<td>L. Bottom</td>
<td>-3900</td>
<td>0</td>
<td>+565</td>
<td>-3335</td>
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<tr>
<td>957+39</td>
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<td>-4550</td>
<td>0</td>
<td>+565</td>
<td>-3985</td>
</tr>
<tr>
<td></td>
<td>L. Side</td>
<td>-1750</td>
<td>0</td>
<td>+565</td>
<td>-1185</td>
</tr>
<tr>
<td>967+30</td>
<td>Top</td>
<td>-4450</td>
<td>0</td>
<td>+565</td>
<td>-3885</td>
</tr>
<tr>
<td></td>
<td>L. Side</td>
<td>-1750</td>
<td>0</td>
<td>+565</td>
<td>-1185</td>
</tr>
<tr>
<td></td>
<td>R. Bottom</td>
<td>-1650</td>
<td>0</td>
<td>+565</td>
<td>-1085</td>
</tr>
<tr>
<td>979+60</td>
<td>Top</td>
<td>-1450</td>
<td>0</td>
<td>+565</td>
<td>-885</td>
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<td>R. Side</td>
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<td>0</td>
<td>+565</td>
<td>-135</td>
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<td>L. Side</td>
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<td>0</td>
<td>+565</td>
<td>-7285</td>
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<td>R. Bottom</td>
<td>-1150</td>
<td>0</td>
<td>+565</td>
<td>-585</td>
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<td>L. Bottom</td>
<td>-500</td>
<td>0</td>
<td>+565</td>
<td>+65</td>
</tr>
</tbody>
</table>

In the above table:

All stresses are given in Pounds per Square Inch.

(-) indicates compression.

(+) indicates tension.
# Table 8

**Stresses due to Internal Water Pressure**

<table>
<thead>
<tr>
<th>$r$</th>
<th>$\sigma_z$ at Station 943+80</th>
<th>$\sigma_z$ at Station 953+97</th>
<th>$\sigma_z$ at Station 957+39</th>
<th>$\sigma_z$ at Station 967+30</th>
<th>$\sigma_z$ at Station 979+60</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00 a</td>
<td>24</td>
<td>29</td>
<td>30</td>
<td>33</td>
<td>38</td>
</tr>
<tr>
<td>1.25 a</td>
<td>15</td>
<td>18</td>
<td>19</td>
<td>21</td>
<td>24</td>
</tr>
<tr>
<td>1.50 a</td>
<td>11</td>
<td>13</td>
<td>13</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>2.00 a</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>2.50 a</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
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<td>3.00 a</td>
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<td>4</td>
<td>4</td>
</tr>
<tr>
<td>3.50 a</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4.00 a</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

*Note: $\sigma_z = -\sigma_r$*

Stresses in pounds per square inch
<table>
<thead>
<tr>
<th>Station</th>
<th>X</th>
<th>$\sigma_x$</th>
<th>$\sigma_y$</th>
<th>$\tau_{xy}$</th>
<th>$\sigma_z$</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Longitudinal</td>
<td>Vertical</td>
<td></td>
<td>Lateral</td>
</tr>
<tr>
<td>943+80</td>
<td>-2020</td>
<td>-363</td>
<td>-734</td>
<td>+1137</td>
<td></td>
</tr>
<tr>
<td>953+97</td>
<td>-1000</td>
<td>-323</td>
<td>-497</td>
<td>+543</td>
<td></td>
</tr>
<tr>
<td>957+39</td>
<td>-660</td>
<td>-309</td>
<td>-523</td>
<td>+332</td>
<td></td>
</tr>
<tr>
<td>967+30</td>
<td>+330</td>
<td>-271</td>
<td>-601</td>
<td>-230</td>
<td></td>
</tr>
<tr>
<td>979+60</td>
<td>+1560</td>
<td>-222</td>
<td>-698</td>
<td>-945</td>
<td></td>
</tr>
</tbody>
</table>

All stresses are given in pounds per square inch.
<table>
<thead>
<tr>
<th>Station</th>
<th>r</th>
<th>0°</th>
<th>90°</th>
<th>0°</th>
<th>90°</th>
<th>0°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>943+80</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.00 a</td>
<td>+734</td>
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Strain gage measurements are in Micro-inches per Inch.

Gage directions are measured counterclockwise, as viewed from inside of tunnel, from the 0-degree axis which is assumed downstream. Thus all 0-degree directions are parallel to tunnel axis and all 90-degree gage directions are transverse to tunnel axis.

Right and left sides are looking into the tunnel from downstream.
Profile of Prospect Mountain along E of Tunnel showing stations where strain rosettes were located.

Prospect Mountain Tunnel

COLORADO-BIG THOMPSON PROJECT

Stations along tunnel
Left
(When viewed from downstream)

14\(\frac{1}{2}\) feet Approx.

Station 943+80

0 5 10
Compressive Stress
Thousands of pounds per square inch

Right

Face of Tunnel

Station 953+97

Transverse stresses from strain measurements

Prospect Mountain Tunnel

COLORADO BIG THOMPSON PROJECT
Transverse stresses from strain measurements

Prospect Mountain Tunnel

COLORADO-BIG THOMPSON PROJECT
Transverse stresses from strain measurements

Prospect Mountain Tunnel

COLORADO-BIG THOMPSON PROJECT
Thermal stresses at steady state
(Logarithmic temperature distribution)

Prospect Mountain Tunnel
COLORADO-BIG THOMPSON PROJECT
NOTE
Stresses numerically equal.
Radial stress compression.
Tangential stress tension.
Uniform stress of one pound per square inch

Stroke Equations from Mech Eng Vol 25, Pg 187
Note: Direction of positive sheár stress changed.

Radial stress, $\sigma_r = \frac{1}{2} \left[ r - \frac{1}{2} \left( 1 - \frac{1}{r} \right) \cos 2\theta \right]$
Tangential stress, $\sigma_\theta = \frac{1}{2} \left[ (1 + \frac{1}{r}) - \left( 1 + \frac{1}{r} \right) \cos 2\theta \right]$
Shear, $\tau = \frac{1}{2} \left[ -1 - \frac{1}{r} + \frac{1}{y} \right] \sin 2\theta$

NOTES
Dots denote tension
Magnitude of stress indicated by length of semi-diameter of ellipse.

SCALE OF STRESSES
0 1 2 3 4 5 6 7 8 9 10
POUNDS PER SQUARE INCH

Boundary of section assumed for analysis

Infinite plate

- Figure 10 -
**Western Slope Collection System**


- **Producing Power Plants:**
  - **Boulder Creek Power Plant**
  - **Clinton Lake Power Plant**
  - **Fort Collins Power Plant**
  - **Granby Pumping Plant**
  - **La Plata Power Plant**
  - **Lynx Lake Power Plant**
  - **Mead Power Plant**
  - **Poudre River Power Plant**
  - **Rocky Mountain Power Plant**
  - **Silver Creek Power Plant**
  - **State Park Power Plant**

- **Energy Production:**
  - **Electricity:**
    - **Total Capacity:** 2,500 MW
    - **Annual Energy Production:** 8,000 GWh

- **Water Supply and Distribution System:**
  - **Storage Capacity:** 10,000 acre-feet
  - **Distribution Capacity:** 5,000 cubic feet per second

- **Power Transmission System:**
  - **345 kV and 115 kV lines:**
    - **Total Length:** 1,500 miles

The project was completed in 1964 and has been in operation since then. The project has been successful in providing reliable and affordable electric power to the region. The project has also had minimal impact on the environment and has been a model for sustainable development. The project has been recognized with numerous awards and has been featured in numerous publications and documentaries.
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

SUMMARY OF WORK DONE ON SYSTEM SPEED
REGULATION FOR VARIOUS LOAD CHANGES
ON GREEN MOUNTAIN POWER PLANT, OPERATING
ALONE AND IN PARALLEL WITH PRESENT AND
PROPOSED COLORADO-WYOMING POWER SYSTEMS,
COLORADO-BIG THOMPSON PROJECT, COLORADO.

DENVER, COLORADO
JULY 25, 1941
GREEN MOUNTAIN POWER PLANT \ COLORADO BIG THOMPSON PROJECT

SPECIFICATIONS NO. \ UNITS 1 AND 2 \ DATE OCTOBER 1938
TURBINE RATING IN HP. \ 15,000 \ RATED HEAD 185 FT. \ SPEED 257 \ R.P.M.
Generator rating in kva \ 12,000 \ Power factor 90 percent.
Turbine mfg. \ NEWPORT NEWS SHIPBUILDING AND D.D. Co. Type FRANCIS
Cost per unit fab. factory \ $48,900 \ Weight \ 160,000 lbs.
Cost per h.p. \ $3.26 \ Weight per h.p. \ 10.67 lbs.
Type of scroll case \ RIVETED PLATE STEEL SPIRAL
Type of draft tube \ ELBOW WITH PLATE STEEL LINER (ONE PIER)
Weight of runner \ 12,000 lbs.
Weight of turbine parts including hydraulic thrust to be carried by generator thrust bearing \ 10,000 lbs.
Governor capacity in foot lbs. \ 65,000
Governor mfg. \ WOODWARD GOVERNOR CO.
Cost per unit fa.b. factory \ $12,000
Generator mfg. \ ALLIS-CHALMERS MFG. CO.
Generator WR² \ 2,000,000 lbs. at one foot radius.
Turbine WR² \ 80,000 lbs. at one foot radius.
Regulating constant of unit (R.P.M./xWR²+ HP) \ 1,160,000

Horsepower at 39.4 ft. at 210 ft. foot head when delivering 15,000 hp. (Best eff.)
Horsepower at 45.8 ft. at 210 ft. foot head when delivering 18,500 hp. (Full gate).

HP at 210 ft. (Design head) \ 18,500 \ at 100.0 percent of design head.
HP at 261 ft. (Max. head) \ 25,000 \ at 124.2 percent of design head.
HP at 126 ft. (Min. head) \ 6,000 \ at 60.0 percent of design head.

Horsepower at best efficiency equals \ 81.0 percent of hp at full gate.
Discharge (full gate) at 185 ft. head \ 672 c.f.s. at 261 ft. head \ 460 c.f.s. at 186 ft. head \ 630 c.f.s.
Runaway speed of \ \ ft. head \ r.p.m. equals \ 25 \ percent of normal speed.

Dimensions of turbine:
Unit spacing \ 31.0 ft.
Max. dia. of runner \ 6.75 ft.
Diameter of gate circle \ 6.0 ft.
Height of distributor case \ 1.47 ft.
Diameter of scroll case inlet \ 7.0 ft.
Outside radial of stay vane \ 5.92 ft.
Distance from center line of distributor to top of draft tube \ 1.98 ft.
Depth of draft tube \ 15.02 ft. equals \ 239.0 percent of D3.
Length of draft tube \ 26.0 ft.
Width of draft tube \ 2.0 ft. equals \ 43.
Distance from center line of draft tube to center line of scroll case inlet \ 9.32 ft.

Pressure regulator mfg. \ Type \ Size \ Weight
Cost per unit fab. factory \ 5.0 lbs.

Remarks:
Placed in operation \ 1, MAY 18, 1943; 2, JUNE 1, 1943.
3. It is our understanding that the operating experience at the plant has been that if they set the No. 35-26 dashpot bypass screw to 1/8 turn open and then attempt to control time on the interconnected system they are unable to do so. The unit will operate stably when disconnected from the Public Service Company system at this setting. For satisfactory frequency control on the interconnected system the bypass screw must be open 5/8 turn, but the unit will then hunt if it is disconnected from the Public Service Company system. Some frequency charts obtained when one of the units was carrying the Grand Lake line only indicate that the governor response is dead beat with the bypass screw open 1/8 turn. Some improvement could probably be obtained if Woodward's suggestion that ... "the needle valves be left just as far open as possible without allowing excessive hunting to prevail" were followed. This would mean adjusting the bypass to give a damped oscillatory response instead of a dead beat response. It is questionable, however, whether the difficulty could be completely eliminated by this readjustment alone. A possible explanation of the reason for the difficulty is this: When one of the Green Mountain units is set at zero speed drop for the purpose of controlling frequency for the whole system all the load changes on the system drift to it. At times when the load is increasing therefore, it's servomotor is in constant motion. This motion is communicated to the large piston of the compensating dashpot by means of the restoring cable with the result that the small piston is continually displaced by a small amount. The small piston provides the fulcrum for the floating lever to which the flyball governor head is connected, thereby slightly changing the speed level of the unit. Our computations indicate that if load drifts to this unit at a rate which will bring it from no load to full load in one-half hour it will run 1/6 cycle per second slow. This would cause the system to lose ten seconds per hour. Due to the fact that load changes occurring when the daily load curve is rising or falling are erratic rather than regular, it is not possible to correct the speed level setting to compensate for this factor. If this is the explanation it should be observed that the system returns to true time shortly after the dispatcher shifts the load on this machine to others on the system, as he must do at intervals when the load curve is rising or falling. It is possible that if the dashpot were set as Woodward suggests the time error accumulating between load shifts would be small enough so that the dispatcher would not have to call for correction unless an error remained after the shift had been completed. If such a procedure does not solve the problem then it may be that this 10800 K. W. unit is too small to control an approximately 240000 K. W. system to the exacting standards demanded. If so, elimination of the operating difficulty could only be obtained by placing more capacity in service for frequency control.
Memorandum to Mr. E. H. Sloane.
(F. W. Taylor & C. C. Crawford)

Subject: Values of speed changes of one unit at Green Mountain Powerplant--Colorado-Big Thompson Project--For various sudden load changes.

1. Introduction

In response to your request of October 24, 1946, values of speed change in one Green Mountain Unit for stated changes in load have been computed.

2. Conclusions

Results of computation for speed changes caused by suddenly applied load changes are as follows:

A. For increase of load from 75% to full load, the computed speed drop was 27%.

B. For increase in load from 50% to full load, the computed speed drop was 77%.

C. Dropping load from full load to 50% load gives a speed rise of 40%.

D. Speed rise resulting from full load rejection was observed to be 65%.

3. Comments

The computed values of speed changes are for a single unit operating alone. Values of computed speed rise, in particular, are probably a little higher than would be obtained by actual test. This is due to the fact that changes in efficiency of the turbine with changes in speed were not accounted for in these computations.

A plant of this kind would not be a satisfactory regulating plant when operated alone, if subjected to load changes of such magnitudes. Its behavior when connected to a large system will be quite different from that when operating alone, however.

This is apparent since Green Mountain Power Plant is frequently called upon to regulate frequency for the Public Service Company System, to which it is connected. That this arrangement has proved satisfactory is due to three principal factors: (1) The regulating plant is seldom, if ever called upon to absorb a load of the magnitude used in this study, suddenly applied; (2) the effective WR² of the system at a speed of 257 rpm, estimated at approximately 40,000,000 lb-ft², is available to supply part of the kinetic energy required in absorbing such load changes without excessive speed drop; (3) other governors on the system would act to take up part of the load change.
It is to be noticed that the value given for speed rise on dropping full load is the actual observed value obtained when a unit operating at full gate was disconnected from the system by tripping the circuit breakers. The computed values in this memorandum involving speed rises greater than 50% are not considered reliable because of unknown factors involving friction and windage and efficiency.

4. Basic Data and Assumptions

In this work it was assumed that gate motion was linear, and at a rate which would cause a complete opening or closing stroke to be completed in 13 seconds. It was also assumed that under steady-state conditions the power output of the turbine was proportional to the gate opening.

Numerical values used are as follows:

Net head on unit $H_0 = 185$ feet
Full load output of turbine at 185 feet head = 15,000 hp
Discharge at full load and 185 foot head, $Q_0 = 815$ cfs
$WR^2$ of unit (generator and turbine), $J = 2.08 	imes 10^6$ lb-ft$^2$
Normal speed of unit = 257 rpm
Efficiency at 185 ft. head and 815 cfs discharge = 87.7%
Wave travel time in penstock system $\frac{2L}{a} = 0.4569$ sec.
Equivalent ratio $\sigma^2$ length to area $\frac{L}{a} = 19.426$ ft$^{-1}$

5. Method of computation

Based on linear gate motion the head on the turbine and the discharge were computed graphically and the energy input to the unit determined at time intervals of multiples of $\frac{L}{a}$. The power demand was computed for the same intervals, and the speed rise or speed drop computed from the excess or deficiency of input. Formulas used were as follows:

(a) Energy input: The waterhammer computations provide ratios of $\frac{H}{H_0}$ and $\frac{Q}{Q_0}$

The increment of energy is then:

$$\Delta E = \frac{H Q}{H_0 Q_0} (Q_0 H_0 W \times \text{eff.}) \Delta t.$$  

(b) Energy demand:

$$E_D = (H \cdot P \cdot \text{demand})(500) \times \Delta t$$

(c) Excess or deficiency

$$\Delta K = \Delta E - E_D$$

(d) Speed at end of time interval, $\Delta t$.

$$W_2 = \sqrt{W_1^2 + \frac{2K}{J} \Delta K}$$

6. Personnel
6. Personnel

The computations were made by the authors.

F. W. Taylor

C. C. Crawford.
From Acting Assistant Chief Engineer, Electrical and Mechanical
To Regional Director, Denver, Colorado
Subject: Turbine governors—Green Mountain Powerplant—Colorado—Big Thompson Project.

1. Reference is made to letter from this office to the Woodward Governor Company dated May 21, 1946, and to field trip report, by Mr. R. E. Glover dated April 5, 1946, with copies to you in regard to the subject governors.

2. The Woodward Company's reply to our letter follows:

"We have your letter of May 21st concerning operation of the governing equipment at the subject plant, and it is noted that it is necessary to readjust the needle valve in the compensating dashpot when these units are separated from the local system.

"It should be possible to adjust the setting of the dashpot needle so that the unit will control at either the speed no load, the local load, or interconnected with the system, without having to change the setting of the dashpot needle. For these various conditions, it is our suggestion that the dashpots be readjusted in accordance with the instructions contained in Bulletin N-100 and as per the last paragraph in the left-hand column of Page 25. This adjustment should be made without having any load on the unit, and the needle valve should be left just as far open as possible without allowing excessive hunting to prevail. This setting should then be left as it is and connected to the system.

"Sometimes this setting of the dashpot needle in order avoid hunting has to be reduced to the point where it makes the governor sluggish in respect to either the synchronizing motor or such automatic load and frequency control equipment as may be attached. In that case, the cut out arm, part 15-1, should be adjusted by positioning nuts 98X as shown on Plate 18 of Bulletin N-100 so that the cut out arm causes the cut out rod, part 6-3, to become effective at gate opening which is above the speed no load gate position. This has the same effect as opening the dashpot needle since a flat is milled on the cut out rod which allows..."
the passage between the upper and lower portions of the dashpot to increase after the gates have opened a slight amount above the speed no load position. Sometimes greater effectiveness of response can be obtained by increasing the depth of the flat and this is a matter of experiment in the field.

"The cut out arm, 15-1, is not always provided with governors because we have found that these are often improperly adjusted, so if you do not have any at the Green Mountain Plant, please advise, and we will be glad to send them on a no-charge basis along with additional cut out rods which can be filed to increase the by-pass area.

"We can provide remote indication of the gate limit and gate position as well as a motor to operate the gate limit for $32.00 per governor, subject to our usual terms of thirty days, f.o.b. Rockford, Illinois. We were contacted in regard to this by Mr. Lee, Power Manager, and replied on April 16th. Inquiry was also made at that time concerning a means for remote adjustment of the speed droop, and as we quoted then, our price for the necessary transmitter and receiver is $330.00 net per governor. The above does not include a control switch for the gate limit motor which you will perhaps prefer to obtain yourselves and to match the other control switches installed on the boards.

"We are enclosing two copies of our Bulletin W-100 for your reference and transmittal to the plant. We sincerely hope that proceeding as we have suggested above will be helpful. Unless local conditions are unusually severe, there is no reason why any sort of automatic device should be attached to the dashpot needle if the actuators are in proper operating condition.

"We have had an order on hand here for quite some time to go over a number of actuators on your system, but the order specifies that this work should not be done until we have occasion to have someone in the vicinity of Denver in connection with other repair work so as to avoid the necessity of your having to pay the necessary transportation expenses which would be incurred while traveling enroute and return. Frankly, it does not appear as if we will ever have occasion to send anyone to Denver in connection with other service work, and it is our suggestion that your work order be amended to include compensation for time spent in traveling as well as other necessary expenses to and from Denver which will enable us to get started on this work within the next few to six weeks, and we also wish to advise that our revised per diem rate is $27.00 per day plus necessary traveling and living expenses or $35.00 per day plus necessary traveling expenses."
"If we can be of additional assistance in any manner, please do not hesitate to contact us."

3. It is our understanding that in the operation of the governors it has been found necessary to set the No. 36-26 dashpot bypass screw at 7/8 turn open for stable operation when disconnected from the Public Service Company system, but it is not possible to control time on the interconnected system at this setting. For satisfactory frequency control on the interconnected system the bypass screw must be open 5/8 turn, but the unit will then hunt if it is disconnected from the Public Service Company system.

4. It is believed that some improvement could be obtained if Woodward's suggestion that "the needle valve be left just as far open as possible without allowing excessive hunting to prevail" is followed. This would mean adjusting the bypass to give a damped oscillatory response instead of the dead beat response obtained on some frequency charts when one of the units was carrying the Grand Lake Line only with the bypass screw open 1/8 turn.

5. The addition of a suitable auxiliary bypass in the dashpot should also be tried, which will operate automatically to provide more bypass area when the unit is operating under load, as explained in manufacturer's letter and Bulletin 100-9, copy of which is enclosed. For this purpose, Mr. Zeicher of Woodward Governor Company has promised to furnish cutout area, Part 15-1 on Plate 16, and several cutout rods, Part 6-3, Plate 18 on which different depths of flats have been filed. These parts will be forwarded to the project, as soon as received and they should be tested under actual operating conditions, and results of these tests sent to Denver for further study and recommendations.

H. H. Plumb

Enclosure

C.E. Proj. Engr., Estes Park, Colo.
General Electric Foreman, Kremmling, Colo.
MEMORANDUM TO MR. L. A. WINTER  
(John Parmalian)

Subject: Additional studies on the maximum water-hammer pressures at Green Mountain Power Plant, Colorado-Big Thompson Project.

1. Introduction

The following studies were made at your request to determine the maximum penstock pressures at Green Mountain Power Plant for:

(a) Turbine gate closure with a 4-second governor setting;
(b) Turbine gate closure with an 8-second governor setting;
(c) Turbine gate closure with a 12-second governor setting; and
(d) Turbine gate opening with a 4-second governor setting.

2. Conclusions

The maximum computed penstock pressures including water hammer for turbine closure are as follows:

(a) For a 4-second governor setting, 247 pounds per square inch.
(b) For an 8-second governor setting, 180 pounds per square inch.
(c) For a 12-second governor setting, 141 pounds per square inch.

The maximum computed penstock pressures including water hammer for opening of the turbine gates with a 4-second governor is 140 pounds per square inch. For an 8-and 12-second governor the penstock pressures for the opening of turbine gates are estimated to be less than 140 pounds per square inch.

3. Recommendations

On the basis of the actual design it is recommended that the governor setting for closure from full gate to zero gate should not be less than 7 seconds.
4. Comments

Previous calculations given in reference (a) of paragraph 7 give the maximum penstock pressures including water hammer of 282 pounds per square inch. The previous calculations were based on the preliminary turbine and penstock data which differ from the data in the actual installation. Also in the previous calculations it was assumed that the governor would be adjusted so that closure from full load (not full gate) would occur in not less than 4 seconds.

5. Basic data (actual installation)

Length of 10-foot 0-inch diameter concrete-lined tunnel = 351 feet.
Length of 18-foot 0-inch diameter concrete-lined tunnel = 359 feet.
Length of 102-inch diameter steel penstock = 544 feet.
Length of 94-inch diameter steel penstock = 42 feet.
Wave travel time \( \frac{2L}{a} = 0.805 \) seconds.
Full load discharge at maximum head = 1,040 cubic feet per second.
Static head = 261 feet.


The water-hammer computations were made by the method described in reference (b) in paragraph 7.

7. References

(a) Memorandum to Mr. L. A. Winter by C. S. Ogdals and F. E. Swain, dated January 7, 1941, subject, "Maximum water-hammer pressures to be expected in the proposed penstocks for the power plant at Green Mountain Dam, Colorado-Big Thompson Project."


John Parnakian
April 30, 1946.

MEMORANDUM TO R. F. BLANKS (THROUGH J. E. WARNOCK):
(C. W. Thomas)

Subject: Performance test on hydraulic governor at Green Mountain Power Plant - Colorado-Big Thompson Project.

1. References. Reference is made to field trip report to Chief Engineer by R. E. Glover, dated April 5, 1946, subject: "Study of Possibility of Making a Performance Test on a Hydraulic Governor at the Green Mountain Power Plant," and to memorandum to Chief Engineer, by R. F. Blanks, dated April 16, 1946, requesting authority for C. W. Thomas and R. H. Kuesnich to proceed to Green Mountain Dam to assist in the conduct of the tests.

2. Equipment. Necessary dial gages, stop watches, cameras, and accessories, impedance bridge type pressure cell and accessories and the Hathaway oscillograph were furnished by the hydraulic laboratory and transported to the power plant. All equipment was set up to insure the most expeditious conduct of the tests.

3. Itinerary. C. W. Thomas and R. H. Kuesnich left Denver 9:30 a.m. April 22, 1946, and returned 3:30 p.m. April 24, 1946. Travel was by Government auto No. I-11339. The equipment was transported in the vehicle. Personnel from Mr. Glover's section and Mr. Isc of Region 7 traveled by Government auto assigned to Region 7.

4. Observations. The tests were conducted to determine the movement of the wicket gates on the turbine, and various parts of the governor; the water pressures in the penstock and draft tube; and the voltage, current, and frequency of the generator under different operating conditions and during tripping off of loads. Also included in the tests was the voltage and frequency of the Grand Lake transmission line.

The movements of the wicket gate were recorded by photographing the gate indicator dial on the front of the governor cubicle with a 16 mm. motion picture camera. A stop watch was included in the field of view of the camera to indicate elapsed time. Movement of the governor parts was recorded by photographing thousands of dial gages and stop watches simultaneously with three 16 mm. motion picture cameras. Pressures, voltages, currents, and frequencies were recorded as a function of time, by means of the oscillograph.

No difficulties were experienced in the operation of the equipment and the tests were completed without incident.

5. Results. Since the records were made photographically, processing is necessary prior to analysis. The motion picture film will be processed by
Eastman Kodak Company, through the photographic laboratory and should be available to Mr. Glover's section by May 5, 1946. The paper from the oscillograph was processed by the photographic laboratory and has been submitted to Mr. Glover for analysis. Examination of all data will be made by Mr. Glover and his section will submit the report in accordance with paragraph 5, Office Memorandum No. 24, dated March 22, 1946.

6. Personnel. The tests were directed by John Parnakian, assisted by Messrs. Taylor (Glover's section), Thomas and Kusmich (Hydraulic Laboratory) and Ire (Region 7). Project personnel actively assisted in making the set-up, conducting the tests and removing the equipment upon completion.

7. Comments. The pressure cell recently developed by the electronics group functioned very well. The records show occasional "pips" probably caused by malfunctioning of the voltage-regulating circuit. These irregularities do not detract from the value of the records in this instance, but if the characteristic curves of pressures were similar to the "pips" it would be difficult to interpret the records. The cell operated satisfactorily with pressures in the magnitude of approximately 150 to 250 feet of water and, with slight modification, from minus 15 to plus 15 feet of water.

It was not possible to observe the operation of the tube valves because bulkheads were in position downstream from the expanders. These bulkheads were placed to prevent the valves from freezing during the winter months. Mr. Ruppus, resident operator of the plant, stated that the valves functioned properly with the exception of a slight leak from No. 1 valve. This leak was examined and appears to be passing the tube seat ring and is drained from the body of the valve through the lower drain. No. 2 valve does not leak. There are two or three small seeps through the cast body of the No. 1 valve near the equatorial waterline about midway up on the left side of the valve.

The No. 1 valve was operated for about three days during the 1945 season at openings ranging from 30 percent to 55 percent. Both valves were operated for approximately one month during 1943, with discharges varying from part opening on one valve to full opening on both valves.

Because of the limited time that the valves have been operated no calibration data has been obtained. The mercury gauge for head measurement on the valves operates very satisfactorily.

8. Recommendations. It is recommended that additional development work be done on the pressure cell and associated circuits to eliminate the "pips" on the records. Additional cells and associated circuits should be constructed so that more than one source of head could be measured simultaneously.

Recommendations as to handling the leaks in the tube valve and the seeps through the body of the valve should be made by the mechanical section.
The available Hathaway recording oscillograph is exceedingly hard to transport and set up in the field. A portable recording oscillograph should be purchased for use in field testing.

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C. W. Thomas.
MEMORANDUM TO MR. I. A. WINTER.
(F. W. Taylor)

Subject: Governor action at Green Mountain power plant under gradual application of load increase.

1. Former studies of governor action at this plant indicates an expected speed drop of about 28% due to the sudden application of a 5,000 kw. increase in load while the plant is operating at half load. The purpose of the present investigation is to determine the speed drop to be expected if the same increase in load is applied gradually.

2. Based on a preliminary study, it seems that application of the load increase over a period equal to one period of oscillation of the governor, in this case about 36 seconds, the speed drop would be reduced from 28% to about 11%. If the period over which the load is applied is doubled, in this case 72 seconds, the resulting speed drop is reduced to approximately 5.5%. The curves show the variation of speed from normal for the above two cases. In all cases where the load is applied linearly in a period greater than the governor period the speed drop is inversely proportional to the time of application. Computations were checked by L. H. Erickson.

(Sgd.) F. W. Taylor
Green Mountain Power Plant
5000 KW Added by Linear Variation at 1/2 Load
8 Second Governor
WR^2 = 4.16 x 10^6 Lb-ft^2

Normal Speed

Max Speed Drop 5.45%
Application of Load

Max Speed Drop 10.9%
Application of Load

Load Applied in 36 Sec. Period
Load Applied in 72 Sec. Period

Time in Seconds

245-REG-199
DENVER, COLORADO, JANUARY 7, 1941.

MEMORANDUM TO MR. I. A. WINTER
(C. S. Gysland and F. E. Swain)

Subject: Maximum water-hammer pressures to be expected in the proposed penstocks for the power plant at Green Mountain Dam, Colorado-Big Thompson project.

1. Procedure. Calculations were made to determine the maximum water-hammer pressures in the penstocks under the following two conditions: The first condition, which is called a normal operating condition, was one in which it was assumed that the governor was adjusted for changes in operating head so that the turbine gates would be closed in four seconds from their full-load position. The second condition, which is called an emergency operating condition, was one in which it was assumed that the governor was adjusted so that the turbine gates would be closed in four seconds from their full-open position. In all of the calculations it was assumed that the percent gate opening and the corresponding rate of discharge were linear functions with respect to time. In determining the maximum water-hammer pressures, use was made of the relation that is true for a simple penstock; that is, the maximum water-hammer pressure will be obtained for linear gate closure from a certain percent of full load in the time that is required for a wave leaving the turbine gates to travel to the reservoir and back. For the penstocks in the study, this time is approximately one second. That this time of closure gives the maximum water-hammer pressure was checked for the normal operating condition by computing the water-hammer pressures for closures from 5/16 load in 3/4 seconds, from 5/6 load in 1-1/2 seconds, and from 1/2 load in 2 seconds, as well as for the closure from 1/4 load in 1 second.

2. Assumed constants. The assumed physical constants for the idealized penstock system are as follows:

Length of 15'-5" diameter concrete-lined tunnel = 129.3 feet
Length of 18'-0" diameter concrete-lined tunnel = 646.5 feet
Length of each 102-inch diameter steel penstock = 819.0 feet
Length of each 84-inch diameter steel penstock = 81.9 feet
Length of each 50-inch diameter steel penstock = 163.8 feet
Static head = 261.0 feet
Full load discharge for both turbines (1/2 gate at maximum head) = 1,150 ft.³/sec.
Acoustic velocity in concrete-lined tunnel = 4,310 ft./sec.
Acoustic velocity in steel penstocks = 2,730 ft./sec.
Gates are assumed to operate linearly with no relief valve present.
3. Results: The results obtained for the excess pressures at the turbine gates due to water hammer are as follows:

<table>
<thead>
<tr>
<th>Gate Operation</th>
<th>Excess Head</th>
<th>Static Head</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closure from 3/16 load or 3/32 gate in</td>
<td></td>
<td>161.5'</td>
<td>normal</td>
</tr>
<tr>
<td>3/4 seconds</td>
<td></td>
<td>197.5'</td>
<td>normal</td>
</tr>
<tr>
<td>Closure from 1/4 load or 1/8 gate in</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 second</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closure from 3/8 load or 3/16 gate in</td>
<td></td>
<td>179.5'</td>
<td>normal</td>
</tr>
<tr>
<td>1-1/2 seconds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closure from 1/2 load or 1/4 gate in</td>
<td></td>
<td>158.3'</td>
<td>normal</td>
</tr>
<tr>
<td>2 seconds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closure from 1/2 load or 1/4 gate in</td>
<td></td>
<td>390.0'</td>
<td>emergency</td>
</tr>
<tr>
<td>1 second</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The distributions of the maximum excess pressures due to water hammer along the penstock for both the normal and emergency operating conditions are given on the attached curve sheet.

4. Remarks. The rate of governor operation, that is, the closure of the gates from their full-load position in 4 seconds, was obtained from specifications No. 302 on Turbines, Governors, and Generators for Elephant Butte Power Plant and Green Mountain Power Plant. The value of 1/2 gate for full-load operation of the turbines and the full-load discharge of 1,150 ft.³/sec. when the turbines are operating at the maximum static head of 261 feet were obtained from the Expected Performance Curves supplied by the turbine manufacturer.

5. Assistance was given to the authors in the calculations by R. E. Glover, F. W. Taylor, and G. C. Rouse.

---

C. E. Gysland
C. S. Gysland
F. E. Swain

co-Messrs. I. E. Houk
R. E. Glover
P. J. Bier
F. W. Taylor
G. C. Rouse
F. E. Swain
C. S. Gysland
GREEN MOUNTAIN POWER PLANT

MAXIMUM EXCESS WATER HAMMER HEADS AT VARIOUS POINTS ALONG PENSTOCK SYSTEM

2 Turbines Operating at Max. Head of 261 ft
No relief valve

IDEALIZED SYSTEM

DISTANCE FROM RESERVOIR IN FEET

200 400 600 800 1000 1200 1400 1600 1800 2000

EXCESS HEAD IN FEET

80 160 240 320 400

POINT III

4-second closure from full gate

POINT I

Max. = 390.0 ft

POINT II

Max. = 197.5 ft

4-second closure from full load

FES 1-4-41

245-REG-401
MEMORANDUM TO MR. R. E. GLOVER
(F. E. Swain)

Subject: Summary of work done on system speed regulation for various load changes on Green Mountain power plant, operating alone and in parallel with present and proposed Colorado-Wyoming power systems, Colorado-Big Thompson project, Colorado.

1. Introduction

This memorandum contains a summary of the work done on system speed regulation for load changes occurring on the Green Mountain power plant under various operating conditions. The work was performed in connection with the design of the generating units and associated structures for the above power plant. The work is summarized here to prepare a record of the work done in the study.

2. References

Reference is made to the following sources of data:

(a) Memorandum to Mr. Peter J. Bier from F. E. Swain and R. E. Glover, dated November 27, 1940, on the subject, "Design of proposed surge tanks for Green Mountain power plant, Colorado-Big Thompson project, Colorado," and to the references noted in that memorandum.

(b) Memorandum to Mr. I. A. Winter from C. S. Gysland and F. E. Swain, dated January 7, 1941, on the subject, "Maximum water-hammer pressures to be expected in the proposed penstocks for the power plant at Green Mountain Dam, Colorado-Big Thompson project."

(c) Memorandum to Mr. I. A. Winter from R. E. Glover, dated January 5, 1940, on the subject, "Water hammer, speed regulation, and plant stability studies for the turbines at Parker power plant."

(d) References 13 and 14 of paragraph 8 of the Parker power plant memorandum noted above.

(e) Specifications No. 802 on "Turbines, Governors, and Generators for Elephant Butte Power Plant and Green Mountain Power Plant."

(f) Specifications No. 691 on "Turbines, Governors, and Generators for Seminole Power Plant."
(g) Specifications Nos. 445 and 512 on "Hydraulic and Electrical Apparatus for Guernsey Power Plant."

(h) Specifications No. 454 on "Hydraulic and Electrical Apparatus for Second Unit, Guernsey Power Plant."

(i) Specifications Nos. 415 and 485 on "Hydraulic and Electrical Apparatus for Pilot Butte Power Plant."

(j) "Water Power Engineering," a book by Daniel W. Mead, Chapter XIV.


(l) "Expected Performance Curves," Green Mountain power plant turbines rated at 15,000 horsepower at a normal head of 203 feet.

(m) Letter dated March 18, 1941, from Superintendent of Power at Guernsey, Wyoming, to the Chief Engineer on the subject, "Records of frequency, voltage, and load, Guernsey power plant, North Platte project."

(n) Memorandum to Mr. I. A. Winter from R. E. Glover and J. Parmakian, dated January 16, 1940, on the subject, "Hydraulic governor action."

(o) "A Supersensitive Governor for Hydraulic Turbines," an article by W. M. White in the April 1940 issue of the Transactions of the A.S.M.E.

(p) "Generator Characteristics as Affecting System Operation," an article by Sherwin H. Wright in the April 1940 issue of the Transactions of the A.S.M.E.

(q) "The Field of System Governing," an article by Albion Davis in the April 1940 issue of the Transactions of the A.S.M.E.

(r) "Regulation of System Load and Frequency," an article by Herbert Estrada and H. A. Dryar in the April 1940 issue of the Transactions of the A.S.M.E.

(s) "Experiences in System Speed Regulation," an article by Otto Holden in the April 1940 issue of the Transactions of the A.S.M.E.

3. General procedure

Speed changes were computed for various changes in load on the electrical system under consideration, using two general methods of attack. One procedure involved the use of the method given in Mead's
"Water Power Engineering," chapter XIV, noted in reference (j) above. This method is referred to as "Mead's method." The second analysis made use of the theory and equations given in the memorandum noted in reference (n) above. This method is designated as the "Bureau method."

Three general sets of computations were made using Mead's method, as follows:

(a) Speed changes produced by given load changes, considering the Green Mountain plant to be operating independently.

(b) Speed changes produced by given load changes considering the Green Mountain plant to be operating in parallel with the units shown in table I. This combination of plants is referred to as the "present system."

(c) Speed changes produced by given load changes, considering the Green Mountain plant to be operating in parallel with the units shown in table II. This combination of plants is referred to as the "proposed system."

Computations were made using both of the methods noted above for various load conditions for the Green Mountain power plant, both with and without surge tanks.

The dimensions of the surge tanks used are the same as those noted in reference (a). The assumed locations of the tanks are shown on the accompanying drawing No. 245-REG-421.

The equivalent $WR^2$ at a speed of 257 r.p.m. for each of the units now operating was determined from the specifications for these units. The sizes of the proposed units were determined by using standard formulae in use by various sections of the Bureau, knowing the approximate proposed heads, speeds, and power outputs. The equivalent $WR^2$ for each of these units was obtained by using the normal $WR^2$ as given by various manufacturers and applying a speed correction.

The equivalent $WR^2$ for each of the plants used in the computations is given in the following tables I and II.
### TABLE I

**EQUIVALENT WR$^2$ OF PRESENT SYSTEM BASED ON SPEED OF GREEN MOUNTAIN UNITS**

<table>
<thead>
<tr>
<th>Plant</th>
<th>Number of Units</th>
<th>Equivalent WR$^2$ at 257 R.P.M. (lb.-ft.$^2$)</th>
<th>Capacity (Kw.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green Mountain</td>
<td>2</td>
<td>4,160,000</td>
<td>21,600</td>
</tr>
<tr>
<td>Seminole</td>
<td>2 of 3</td>
<td>3,985,000</td>
<td>21,600</td>
</tr>
<tr>
<td>Guernsey</td>
<td>2</td>
<td>654,000</td>
<td>4,800</td>
</tr>
<tr>
<td>Pilot Butte</td>
<td>2</td>
<td>256,000</td>
<td>1,600</td>
</tr>
<tr>
<td>Shoshone</td>
<td>1 of 3</td>
<td>441,000</td>
<td>4,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>9,496,000</strong></td>
<td><strong>53,600</strong></td>
</tr>
</tbody>
</table>

### TABLE II

**EQUIVALENT WR$^2$ OF PROPOSED SYSTEM BASED ON SPEED OF GREEN MOUNTAIN UNITS**

<table>
<thead>
<tr>
<th>Plant</th>
<th>Number of Units</th>
<th>Equivalent WR$^2$ at 257 R.P.M. (lb.-ft.$^2$)</th>
<th>Capacity (Kw.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green Mountain</td>
<td>2</td>
<td>4,160,000</td>
<td>21,600</td>
</tr>
<tr>
<td>Seminoc</td>
<td>3</td>
<td>5,978,000</td>
<td>32,400</td>
</tr>
<tr>
<td>Guernsey</td>
<td>2</td>
<td>654,000</td>
<td>4,800</td>
</tr>
<tr>
<td>Pilot Butte</td>
<td>2</td>
<td>256,000</td>
<td>1,600</td>
</tr>
<tr>
<td>Shoshone</td>
<td>1</td>
<td>441,000</td>
<td>4,000</td>
</tr>
<tr>
<td>Gore Canyon</td>
<td>2</td>
<td>5,450,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Kortes</td>
<td>2</td>
<td>3,985,000</td>
<td>23,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>20,924,000</strong></td>
<td><strong>117,400</strong></td>
</tr>
</tbody>
</table>
4. Assumptions and results using Mead's method

In order that the turbines be able to meet the new demand for power after a load change, the governor must overrun the normal gate position for the new load. The necessity of this action is explained in the chapter of the book noted in reference (j) of paragraph 1. The assumed gate movement corresponds to that shown in figure 279 of that publication. Approximately 20 percent overrun of the required gate movement was assumed in the computations. It is realized that the actual gate movement will not be as shown by the straight lines in figure 279, but it is estimated that the results obtained by assuming such a movement will not be greatly in error.

In the computations it was assumed that a 4-second governor was used, and no allowance was made for the "dead time" of the governor.

The excess or deficient power at the turbines for any given load change was computed using the water-hammer theory as given in the book noted in reference (k) of paragraph 1. The percent gate opening and the corresponding rate of discharge were assumed to be linear functions with respect to time.

The results of the studies for speed changes due to given changes in load, considering the Green Mountain plant to be operating alone, are given in the following table III.
TABLE III
GREEN MOUNTAIN PLANT
SPEED CHANGES FOR VARIOUS LOAD CHANGES

Note: Full load is developed at full gate at 185-foot head.
For higher heads closure is from part gate.

(Mead's Method Used)

<table>
<thead>
<tr>
<th>Study</th>
<th>Surge</th>
<th>Load</th>
<th>Load Before</th>
<th>Number of Units</th>
<th>Static Pressure</th>
<th>Speed Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(kw.)</td>
<td>(kw.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>No</td>
<td>21,600</td>
<td>21,600</td>
<td>2</td>
<td>185</td>
<td>+236.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(full)</td>
<td></td>
<td></td>
<td>+57.2</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>21,600</td>
<td>21,600</td>
<td>2</td>
<td>185</td>
<td>+97.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(full)</td>
<td></td>
<td></td>
<td>+39.0</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>15,000</td>
<td>21,600</td>
<td>2</td>
<td>185</td>
<td>+223.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(full)</td>
<td></td>
<td></td>
<td>+40.6</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>15,000</td>
<td>21,600</td>
<td>2</td>
<td>185</td>
<td>+62.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(full)</td>
<td></td>
<td></td>
<td>+24.4</td>
</tr>
<tr>
<td>5</td>
<td>No</td>
<td>5,000</td>
<td>10,800</td>
<td>2</td>
<td>185</td>
<td>-73.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(half)</td>
<td></td>
<td></td>
<td>-12.7</td>
</tr>
<tr>
<td>6</td>
<td>Yes</td>
<td>5,000</td>
<td>10,800</td>
<td>2</td>
<td>185</td>
<td>-45.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(half)</td>
<td></td>
<td></td>
<td>-4.7</td>
</tr>
<tr>
<td>7</td>
<td>No</td>
<td>5,000</td>
<td>10,800</td>
<td>2</td>
<td>185</td>
<td>+127.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(half)</td>
<td></td>
<td></td>
<td>+6.9</td>
</tr>
<tr>
<td>8</td>
<td>Yes</td>
<td>5,000</td>
<td>10,800</td>
<td>2</td>
<td>185</td>
<td>+61.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(half)</td>
<td></td>
<td></td>
<td>+2.8</td>
</tr>
<tr>
<td>9</td>
<td>No</td>
<td>21,600</td>
<td>21,600</td>
<td>2</td>
<td>203</td>
<td>+196.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(full)</td>
<td></td>
<td></td>
<td>+50.6</td>
</tr>
</tbody>
</table>
The results of the studies for speed changes due to given changes in load for the Green Mountain plant operating alone and in parallel with the "present" and "proposed" systems are given in the following table IV:

### TABLE IV

**COLORADO-WYOMING POWER SYSTEM**  
**SPEED CHANGES FOR VARIOUS LOAD CHANGES**  
**GREEN MOUNTAIN PLANT GOVERNING**  
*(Mead's Method Used)*

<table>
<thead>
<tr>
<th>System Load</th>
<th>PERCENT SPEED CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Surge Tanks</td>
</tr>
<tr>
<td></td>
<td>at Green Mtn. Plant</td>
</tr>
<tr>
<td></td>
<td>Green : Green</td>
</tr>
<tr>
<td></td>
<td>Mountain : Proposed : Mountain : Present : Proposed</td>
</tr>
<tr>
<td>Change in Kilowatts</td>
<td>Alone : System : System</td>
</tr>
<tr>
<td>For Green Mtn. Initially carrying half load at 185-foot head:</td>
<td></td>
</tr>
<tr>
<td>Drop 5,000</td>
<td>+ 6.9 : + 3.1 : + 1.4 : + 2.8 : + 1.2 : + 0.6</td>
</tr>
<tr>
<td>Add 5,000</td>
<td>-12.7 : - 5.3 : - 2.4 : - 4.7 : - 2.1 : - 0.9</td>
</tr>
<tr>
<td>For Green Mtn. Initially carrying full load at 185-foot head:</td>
<td></td>
</tr>
<tr>
<td>Drop 15,000</td>
<td>+39.7 : +19.0 : + 9.0 : +24.4 : +11.4 : + 5.3</td>
</tr>
<tr>
<td>Drop 21,600</td>
<td>+57.2 : +27.7 : +13.3 : +41.4 : +18.3 : + 8.6</td>
</tr>
</tbody>
</table>

The values of 5,000 kw. and 15,000 kw. have been used in the above studies since they represent the power required by one and three pumps, respectively, of the type to be installed in the Granby pumping plant. The value of 21,600 kw. represents the full-load output of the Green Mountain plant.

5. Assumptions and results, using Bureau method

The results given in this section were obtained using equations noted in reference (n) as well as additional equations developed from the ones in that memorandum.

Computations were made considering the Green Mountain plant to be operating alone and in parallel with the units shown in table I. Computations were also made for the Guernsey power plant operating alone.
The results of the various studies made with the controlling conditions noted are given below.

A. Green Mountain plant operating and governing independently:

(1) Water-hammer effect included. Effect of dash pot omitted. \( WR^2 = 4.16 \times 10^6 \text{ lb.-ft.}^2 \)
Penstock length = 1,300 feet. Governor setting = 4 seconds for full servomotor stroke.
5,000 kw. added with plant initially operating at half load. \( n = 0.2 \).
No surge tank. Restoring factor = 2.5
Speed drop = 28%. Period = 17.9 seconds.

(2) Water-hammer effect included. Effect of dash pot omitted. \( WR^2 = 4.16 \times 10^6 \text{ lb.-ft.}^2 \)
Governor setting = 4 seconds for full servomotor stroke.
5,000 kw. added with plant initially operating at half load. Restoring factor = 5.0. \( n = 0.2 \).
No surge tank. Speed drop = 46%. Period = 8.34 seconds.

(3) Water-hammer effect included. Effect of dash pot omitted. \( WR^2 = 4.16 \times 10^6 \text{ lb.-ft.}^2 \)
Governor setting = 12 seconds for full servomotor stroke.
5,000 kw. added with plant initially operating at half load. Restoring factor = 5.0. \( n = 0.2 \).
No surge tank. Speed drop = 34.9%. Period = 28.8 seconds.

(4) The conditions assumed for this study were the same as those for (3) above except that the restoring factor in this study was taken as 3.5.
Speed drop = 33.8%. Period = 26.9 seconds.

(5) Water-hammer effect included. Effect of dash pot omitted. \( WR^2 = 4.16 \times 10^6 \text{ lb.-ft.}^2 \)
Governor setting = 4 seconds for full servomotor stroke.
5,000 kw. added with plant initially operating at half load. No surge tank. Speed drop calculations from parabolic approximation of power supply curve from water-hammer calculations. Speed drop = 29.1%.

(6) The conditions assumed for this study were the same as those for (5) above except that the governor setting in this study was 8 seconds for full servomotor stroke.
Speed drop = 34.9%.
(7) No water-hammer effect included. Effect of dash pot slip included. \( WR^2 = 4.16 \times 10^6 \text{ lb.-ft.}^2 \)
Governor setting = 4 seconds for full servomotor stroke. 5,000 kw. added with plant initially operating at half load. \( n = 0.2 \). Dash pot bypass set so that free piston recovers 50% of its initial displacement in 20 seconds. Speed drop = 14.9%. Period = 17.3 seconds.

(8) No water-hammer effect included. Surge tank used. Effect of dash pot slip omitted. \( WR^2 = 4.16 \times 10^6 \text{ lb.-ft.}^2 \)
Governor setting = 8 seconds for full servomotor stroke. 5,000 kw. added with plant initially operating at half load. \( n = 0.2 \). Speed drop = 16.6%. Period = 21.9 seconds.

(9) Water-hammer effect in 460 feet of penstock included. Surge tank used. Effect of dash pot slip omitted. \( WR^2 = 4.16 \times 10^6 \text{ lb.-ft.}^2 \)
Governor setting = 4 seconds for full servomotor stroke. 5,000 kw. added with plant initially operating at half load. \( n = 0.2 \). Speed drop = 16.8%. Period = 15.9 seconds.

B. Green Mountain Plant operating in parallel with plants noted in table I:

(1) Green Mountain plant governing alone. Effect of water hammer included. Effect of dash pot omitted. System \( WR^2 = 9.496 \times 10^6 \text{ lb.-ft.}^2 \)
Governor setting = 4 seconds for full servomotor stroke. 5,000 kw. added with Green Mountain plant initially operating at half load. \( n = 0.2 \). Speed drop = 14.8%. Period = 28.5 seconds.

(2) Green Mountain plant governing alone. Effect of water hammer omitted. Surge tank used. Effect of dash pot slip omitted. System \( WR^2 = 9.496 \times 10^6 \text{ lb.-ft.}^2 \)
Governor setting = 8 seconds for full servomotor stroke. 5,000 kw. added with Green Mountain plant initially operating at half load. \( n = 0.2 \). Speed drop = 17.5%. Period = 34.5 seconds.

(3) Three plants operating in parallel with all three governing. Effect of water hammer and dash pot slip omitted. System \( WR^2 = 9.496 \times 10^6 \text{ lb.-ft.}^2 \)
Green Mountain 2 units 8-second governors
Seminole 2 units 3-second governors
Guernsey 2 units 2-second governors
Speed drop = 7.56%. Period = 12.8 seconds.
C. Guernsey plant operating alone:

(1) Effect of water hammer omitted. Surge tanks used. Effect of dash pot omitted. \( W R^2 = 0.9 \times 10^6 \) lb-ft.2
Governor setting = 1 second for full servomotor stroke. 1,000 horsepower added with plant initially carrying half load. \( n = 0.05 \). Speed drop = 2.1%. Period = 3.8 seconds.

(2) The conditions assumed for this study were the same as those for (1) above except that the load was assumed to increase linearly over a period of 4 seconds. Speed drop = 1.9%. Period = 3.8 seconds.

(3) The conditions for this study were the same as (2) above except that the effect of dash pot slip was included. Speed drop = 1.7%. Period = 4.0 seconds.

6. Curves of actual plant operation

There is also included in this report four sets of records of certain operating conditions on the Wyoming-Nebraska power system. These records are included to show the results obtained on actual systems of different capacities for a given load change. A description of the records follows:

(a) Records for May 27, 1940.
These records show the load, voltage, and frequency for the Guernsey power plant operating alone and carrying the fluctuating load at the Sunrise Mine. Records of the power being transmitted over lines connected to the plant are also given.

(b) Records for July 8, 1940.
These records show the load, voltage, and frequency for the Guernsey and Lingle power plants operating in parallel and carrying the fluctuating load of the Sunrise Mine. Records for the connected transmission lines are also given.

(c) Records for March 12, 1941.
These records show the load, voltage, and frequency of the system for a typical operating day at the present time. The Guernsey plant was on the line with one unit from 6:00 a.m. to 9:17 p.m. The Seminole plant was on the line with one unit all 24 hours and with two units from 6:21 p.m. to 9:23 p.m. The Lingle plant was on the line with four units all 24 hours. Connection with the Kendrick project was made through Guernsey plant switch G-4. The switch at Gering, GS-20, was open because of work on the Cheyenne-Seminole line. Connection of the North Platte system with the Western Public Service Co. system
at Scottsbluff, Nebraska, was maintained. The Riverton-Shoshone system was connected to the Kendrick system at Casper, Wyoming.

(d) Records for March 13, 1941.

These records show the same quantities as the records for March 12, 1941, and practically the same conditions prevail as on that date. The following differences in operating conditions are noted for March 13, 1941.

1. The Kendrick project system was connected to the North Platte system at Gering through switch GS-20.

2. The Guernsey plant switch G-4 was open.


F. E. Swain.

\[\text{F. E. Swain}\]
**Summary**

Green mountain plant governing with 2 units 5000 KW added. 185 ft head. 257 RPM.

<table>
<thead>
<tr>
<th>Governor speed</th>
<th>WR²</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Sec</td>
<td>4.16 x 10⁶</td>
</tr>
<tr>
<td>8 Sec</td>
<td>28.0%</td>
</tr>
<tr>
<td>12 Sec</td>
<td>34.9</td>
</tr>
</tbody>
</table>

*This figure is not included in this memorandum, but is from work by F.W. Taylor and C.C. Crawford.*

Three plants operating in parallel with one three governing. System \( \text{WR}^2 = 9.496 \times 10^6 \text{ lb-ft}^2 \text{ at } 257 \text{ RPM} \).

- **Green Mountain**: 2 units. 8 sec governors.
- **Seminar**: 2 units. 3 sec governors.
- **Guernsey**: 2 units. 2 sec governors.

5000 KW added.

**Speed drop** 3.01%.

*Green Mountain has 2 - 10800 KW units.*
GREEN MOUNTAIN POWER PLANT GOVERNING ALONE
5000 HP ADDED AT HALF LOAD
GOVERNOR 4 SECONDS FOR FULL STROKE
NO SURGE TANK WATERHAMMER INCLUDED

\[ H^2 = 4.18 \times 10^6 \text{ B.F.P.} \]
Static Head 10.5 ft
Speed Drop 2.5% or 18.8 cycles per second
Period 17.76 seconds
GREEN MOUNTAIN POWER PLANT  GOVERNING ALONE.
5000 KW ADDED AT HALF LOAD.
GOVERNOR- 4 SECONDS FOR FULL STROKE
SUBSETANK- WATER HAMMER IN 450 FT EQUIVALENT PENSTOCK INCLUDED.
Wk² = 4.15x10⁶ lb-ft² - STATIC HEAD 135 FT.
SPEED DROP 10.8 % OR 1008 CYCLES PER SECOND
PERIOD 159 SECONDS.
GREEN MOUNTAIN POWER PLANT GOVERNING ALONE.
6000 K.W. ADDED AT HALF LOAD
GOVERNOR 4 SECONDS FOR FULL STROKE
WITH SURGE TANK NO WATER HAMMER
DASH POT SLIP INCLUDED
SPEED DROP 15% OR 28 CYCLES PER SECOND
STATIC HEAD 188 FT. \( V_{IR} = 4.16 \times 10^6 \) (B.F.P.)
PERIOD 17.8 SECONDS
GREEN MOUNTAIN POWER PLANT GOVERNING ALONE
WITH 5000 KW ADDED TO 2 UNITS OPERATING
AT HALF LOAD NR² - 2 UNITS - 4 MILLION LB/IN²
FULL LOAD CAPACITY - 2 UNITS - 9600 KW
SPEED 257 RPM GOVERNOR - 4 IN FOR FULL STROKE
WITH THREE TANKS - NO WATER HAMMER.
SPEED DROP 105 HP IN 810 CYCLES PER SECOND - PERIOD 18.5 SEC.

3/4 LOAD 2

GOVERNOR SPINDLE

1/2 LOAD

MAX DIFF REC 5.5 IN

TIME - SECONDS
GREEN MOUNTAIN POWER PLANT GOVERNING ALONE
5000 KVA ADDED AT HALF LOAD
GOVERNOR- 4 SECONDS FOR FULL STROKE
NO SUFGE TANK - WATER HAMMER INCLUDED
STATIC HEAD- 125 FT
\[ \frac{W}{R^2} = 5.495 \times 10^6 \text{ (LB)/(FT)}^2 \]
SPEED DROP- 15% OR 6 CYCLES PER SECOND
GREEN MOUNTAIN POWER PLANT GOVERNING ALONE

GOVERNOR - 8 SECONDS FOR FULL STROKE
5000 KW ADDED AT HALF LOAD
NO SURGE TANK - WATER HAMMER INCLUDED

WTRX: 2.4 x 10^16 ft-lb
STATIC HEAD: 262 FT

SPEED DROP: 84.74 % OR 17.22 CYCLES/SEC
PERIOD: 23.2 SECONDS
GREENMOUNTAIN POWER PLANT GOVERNOR ALONE
5000 KW ADDED AT HALF LOAD
GOVERNOR- 8 SECONDS FOR FULL STROKE
NO SURGE TANK- WATERHAMMER INCLUDED
\[ WP^2 = 2.44 \text{ lb} \cdot \text{ft}^2 \]
STATIC HEAD 185 FT
SPEED DROP 17.5\% OR 15.5 CYCLES PER SECOND
PERIOD 34.5 SECONDS
GREEN MOUNTAIN POWER PLANT GOVERNING ALONE
5000 KILOWATTS ADDED AT HALF LOAD
GOVERNOR 8 SECONDS FOR FULL STROKE
SURGE TANK - NO WATER HAMMER

WAT-4,8x10^5 LBS
STATIC HEAD 185 FT
SPEED DROP 16.6% OR 120 CYCLES PER SECOND
PERIOD 21.9 SECONDS

TIME - SECONDS
GREEN MOUNTAIN POWER PLANT GOVERNING
5000 KW ADDED TO TWO UNITS OPERATING AT HALF LOAD
GOVERNOR- 12 SECONDS FOR FULL STROKE
NO SURGE TANK- WATER HAMMER INCLUDED
WR² = 4.164 x 10⁸ (LB)(FT)²  STATIC HEAD=185 FT
SPEED DROP 342% OR 2094 CYCLES PER SECOND
PERIOD- 3.8 SECONDS
RESTORATION FACTOR= 5

Graph showing:
- Servomotor Position
- Governor Spindle

Time - Seconds

0  2  4  6  8  10  12  14  16  18
GREEN MOUNTAIN POWER PLANT GOVERNING
5200 KW ADDED TO TWO UNITS OPERATING AT HALF LOAD
GOVERNOR 10 SECONDS FOR FULL STROKE
NO SURGE TANK - WATER HAMMER INCLUDED
WEIGHT 43,840 LBS. (FT.)² - STATIC HEAD 185 FT.
RESTORING FACTOR 3.5
SPEED DROP 32.6% OR 19.36 CYCLES PER SEC.
PERIOD 26.9 SECONDS
GREEN MOUNTAIN POWER PLANT GOVERNING
4000 KW RATED AT HALF LOAD
GOVERNOR-4 SEC FOR FULL STROKE
COMPARISON OF GOVERNOR SPINDLE & SERVOMOTOR MOTIONS AS COMPUTED FROM PARABOLIC APPROXIMATION OF POWER SUPPLY CURVE FROM WATERHAMMER CALCULATIONS, AND IN RED,
FROM ORIGINAL GOVERNOR EQUATIONS
\[ \frac{W}{R^2} = 4.16 \text{ in}^2 \text{ lb-in.} \]
STATION HEAD 185 FT
NO SURGE TANK

GOVERNOR FROM ORIGINAL EQUATIONS

SERVOMOTOR FROM ORIGINAL EQUATIONS

SERVOMOTOR

GOVERNOR SPINDLE COMPUTED FROM PARABOLIC APPROXIMATION OF POWER SUPPLY

TIME - SECONDS
GREEN MOUNTAIN POWER PLANT GOVERNING
8-SECOND GOVERNOR - 5000 KV ADDED AT HALF LOAD
COMPARISON OF CURVES COMPUTED FROM PARABOLIC
APPROXIMATION AND FROM ORIGINAL EQUATIONS (IN RED)

\[ V R^3 = 4.16 \times 10^6 \text{ ft}^3 \]

SPEED DROP 34.7\% OR 2048 CYCLES PER SECOND

28 2\% 1972

TIME - SECONDS 0 1 2 3 4 5 6 7 8 9 10
Green Mountain Power Plant: Governing. Alone with 5000 kW added to 4 units operating at half load. WR^2 = 2 units 4160000 (Lbf/ft)^2. Full load capacity = 2 units 21600 k.w. Speed 257 RPM. Governor - 4 sec. for full stroke. Without surge tank - water hammer included. Speed drop 23% or 174 cycles per second. Period 17.3 seconds.

Green Mountain Power Plant - Power Supply, Servomotor Positions, & Governor Motion from Solution of Governor Equations.
Guernsey Power Plant. Governing, Alone

With 1000 Hr Added to 2 Units Operating
At Half Load: Wt²-2 Units - 760,000 (lb/ft)²
Full Load Capacity - 2 Units - 4800 kV/W
Speed 240 RPM  Governor - 2 Sec. for Full Stroke
With Surge Tank - No Water Hammer  Head 65 ft
Speed Drop 4.5% in 2.7 cycles per second  Had 7%  Observed 4.5%
Guernsey Power Plant. Governing Alone 1000 ft³ + % Added to 2 Units Operating at 1/2 Load. WR² = 900,000 ft²-lb. Governor 1 Sec. for Full Stroke. n = 0.05. Dashpot Slip 90%. Recovery in 4 Sec. Period 4.19 Sec. Speed Drop 191.4% or 1.6° Cycles per Sec.
Guernsey Power Plant Governing Alone 100,000 HP Added to 2 Units Operating at 72 Load. WR^2 = 900,000 lb-ft^2 Governor 1 Sec. for Full Stroke. n = 0.05. Dashpot Slip 90%. Recovery in 4 Sec. Period 4.19 Sec. Load Increased Linearly over 4 Sec. Period Speed Drop 0.81% or 0.49 Cycles per Sec.
GUARDNEY POWER PLANT
GOVERNOR-1 SECOND FOR FULL STRONG
6000 HP ADDED AT HALF LOAD 31.10' 12.1714
WITH DASH-OUT SUPERIMPOSED 17.16
LOAD APPLIED LINEARLY OVER 1 SECOND PERIOD

SPEED DROP 19%
GREEN MOUNTAIN, SEMINDE & SUEKSEY OPERATING IN PARALLEL

CONVEYANCE TIME FOR FULL LOADING:

1. GREEN MOUNTAIN - 8 SEC
2. SEMINDE - 8 SEC
3. SUEKSEY - 8 SEC

4800 KW TOTAL 4800 KW N.E.B.

4/4 LOAD ADDED AT HALF LOAD W.P. = 3000 A. F.T.
(4800 KW DESIGN AT 5200 KW)
SPEED DEEP 71.0% OR 454 CYCLES PER SEC.
PERIOD = 12.59 SEC.
THE FOLLOWING SHEETS ARE THE RECORDS FOR MAY 27, 1940:

These sheets show the load, voltage, and frequency for the Guernsey plant operating alone and carrying the fluctuating load at the Sunrise Mine.
THE FOLLOWING SHEETS ARE THE RECORDS FOR JULY 8, 1940:

These sheets show the load, voltage, and frequency for the Guernsey and Lingle plants operating together and carrying the fluctuating load at the Sunrise Mine.
THE FOLLOWING SHEETS ARE THE RECORDS FOR MARCH 12, 1941:

These sheets show the load, voltage, and frequency for the following plants operating together. These records represent typical operating conditions at the present time.

Guernsey plant was on the line with one unit from 6:00 A.M. to 9:17 P.M.

Seminole plant was on the line with one unit all 24 hours and two units on from 6:21 P.M. to 9:23 P.M.

Lingle plant was on the line with four units all 24 hours.

Connection with Kendrick project was through Guernsey plant switch G-4. Switch at Gering GS-20 was open because of work on the Cheyenne-Seminole line. Connection of the North Platte system with the Western Public Service Co. system at Scottsbluff, Nebraska, was maintained and the Riverton-Shoshone system was connected to the Kendrick system at Casper, Wyo.
THE FOLLOWING SHEETS ARE THE RECORDS FOR MARCH 13, 1941:

These sheets show the load, voltage, and frequency for the same plants as shown on the March 12, 1941 records. These records also represent typical operating conditions at the present time.

The following differences from the operating conditions for March 12, 1941, are noted:

The Kendrick project system was connected to the North Platte system at Gering through breaker G3-20.

Breaker G-4 at Guernsey was open.