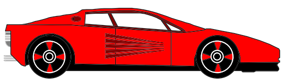
EXERGEN

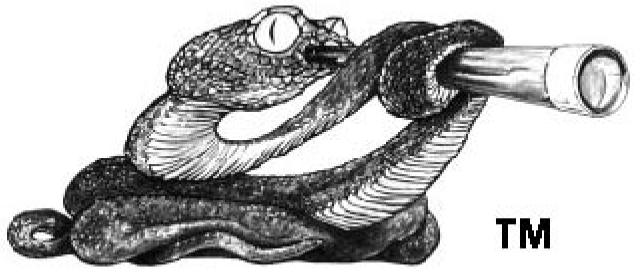
CORPORATION

Specializing in Thermal Management via IR Sensing



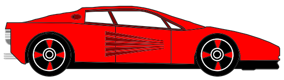
EXERGEN

CORPORATION



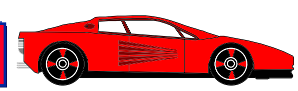
Industrial Division

EXERGEN*IR* Sensors

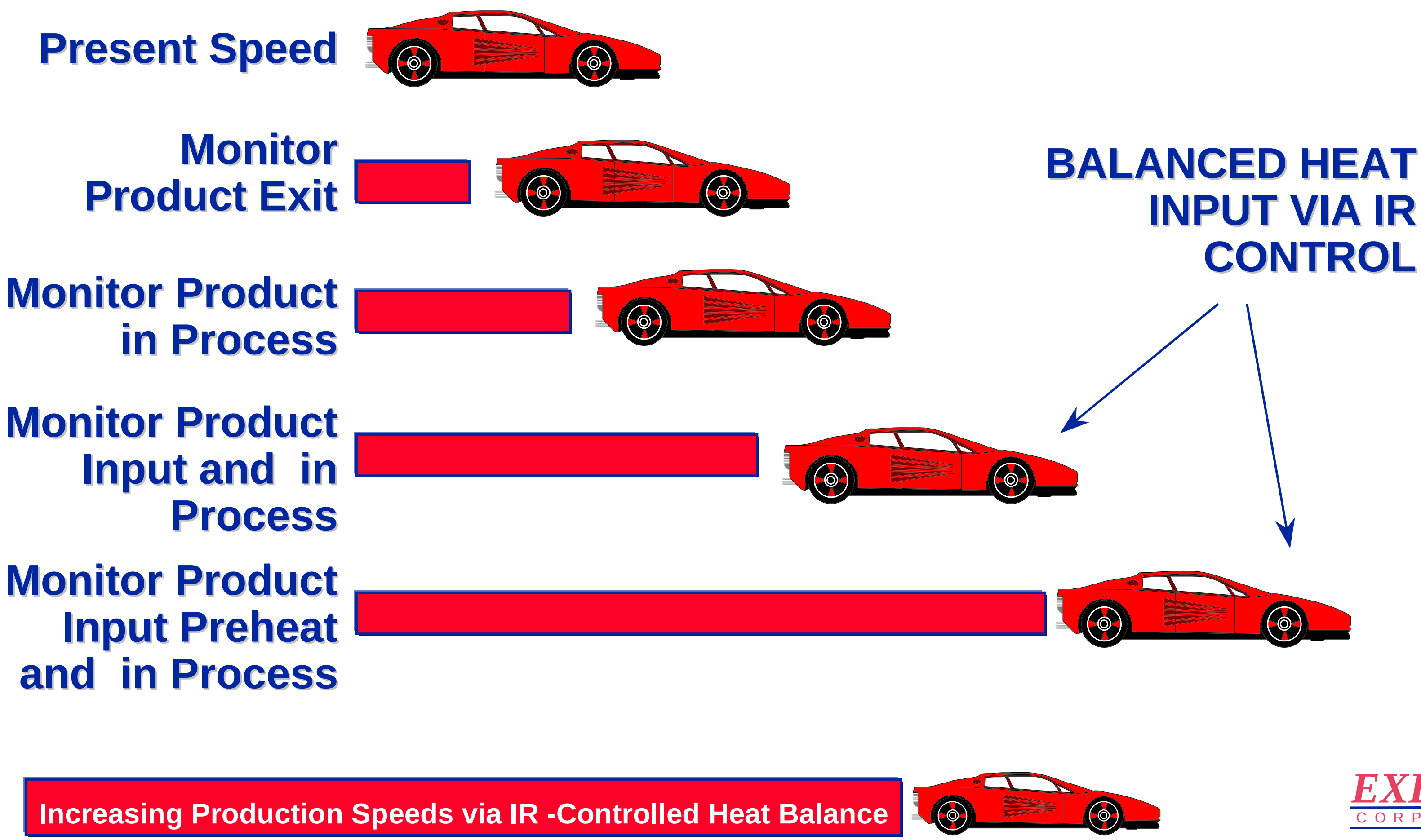


Increasing Production Speeds via Heat Balance Control With IR Sensing

From Fundamentals to Frontiers



Speed Increase Stages



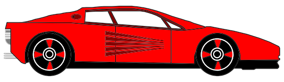
EXERGEN
CORPORATION

Fundamentals

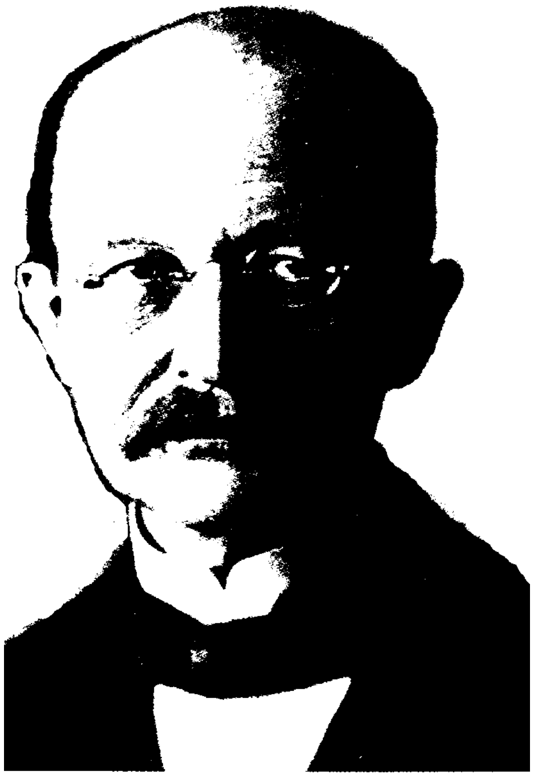
- **Infrared Physics and Math (Briefly)**
- **Emissivity High and Low**
- **Principles of the IRt/c in Non-Contact Temperature Measurement**
- **Heat Transfer Physics and Math (Briefly)**

Frontiers

- Principles of the Heat Balance in Time and Space
- The Speed Boost Equation
- Balanced Heat Input via IR Control
- Applications
  - Laminating, Drying, Printing, Heat Sealing, Color Copying
- High Speed Event Detection

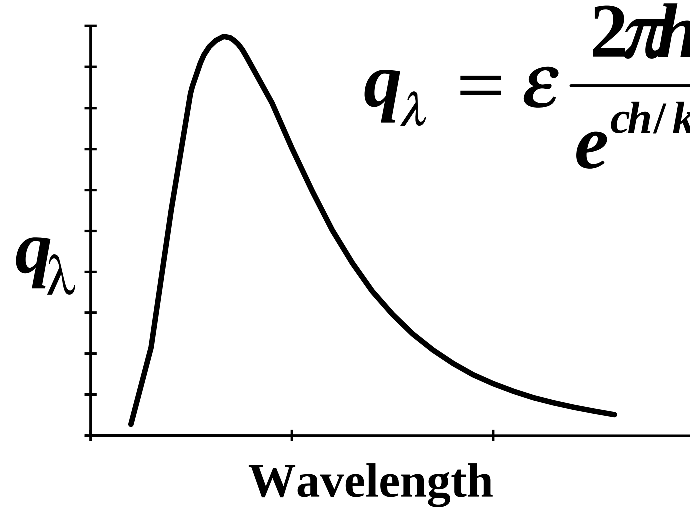


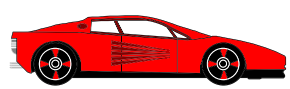
Max Planck ~ 1900



- Desparation Move to Explain Black Body Radiation
- Mathematical Equation for Thermal Radiation Using Quanta

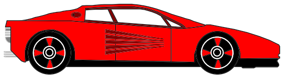
$$q_\lambda = \varepsilon \frac{2\pi hc^2 \lambda^{-5}}{e^{ch/k\lambda T} - 1}$$



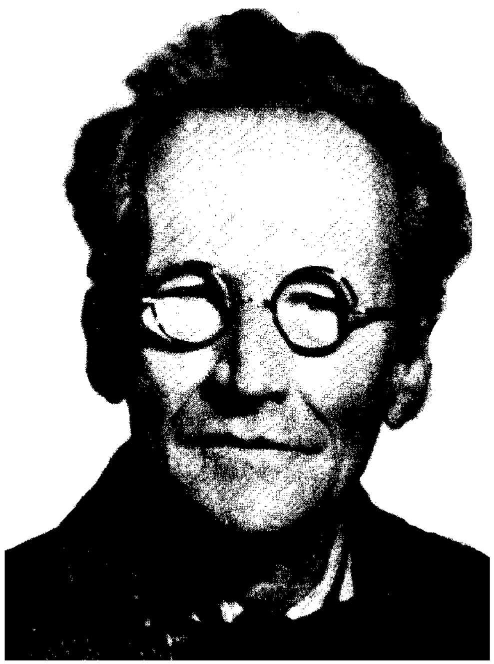


Albert Einstein ~ 1905

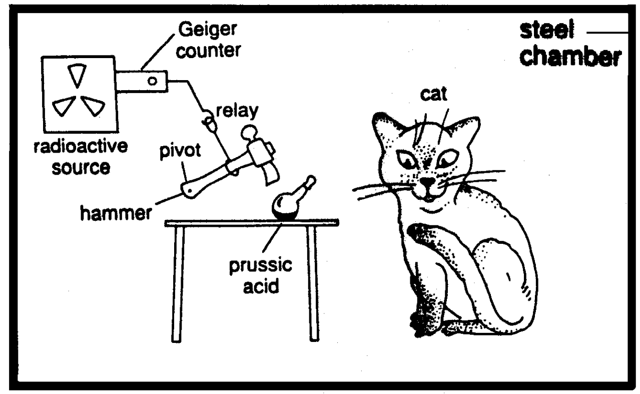
- Confirmed Planck's Quanta by Explanation of Photoelectric Effect
- But Never Really Liked the Eventual Result

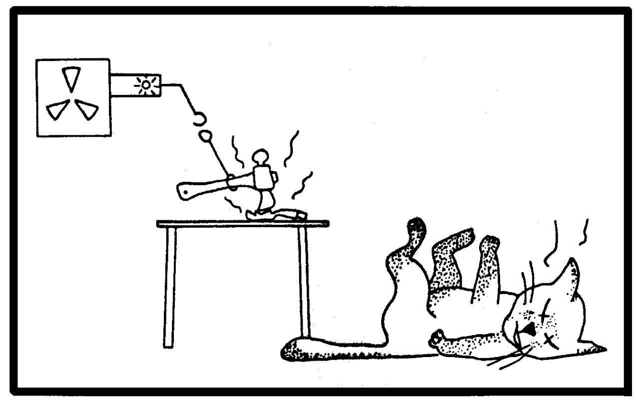


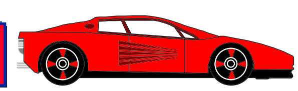
Erwin Schrodinger ~ 1935



- **The Cat Paradox**

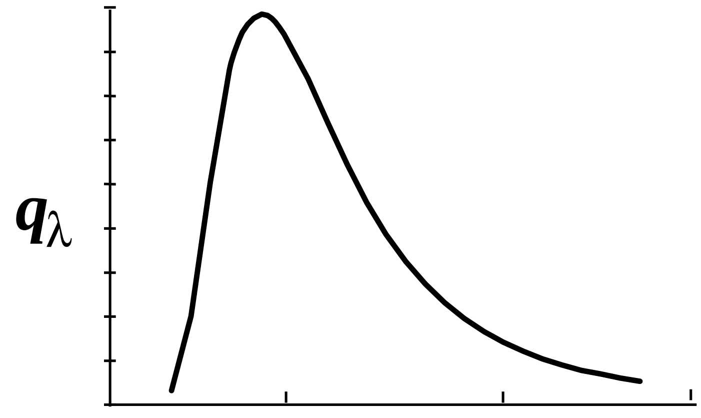






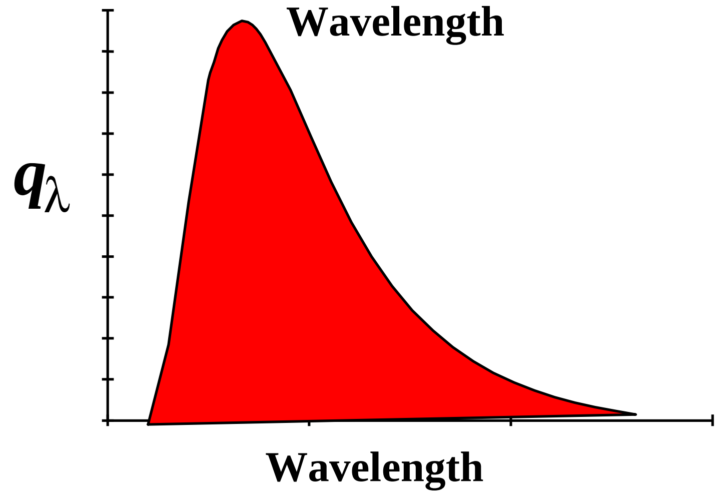
Basic Infrared Equations

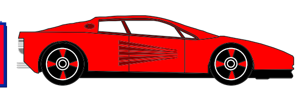
$$q_\lambda = \frac{2\pi hc^2\lambda^{-5}}{e^{ch/k\lambda T} - 1}$$



$$q = \int_0^\infty q_\lambda \, d\lambda$$

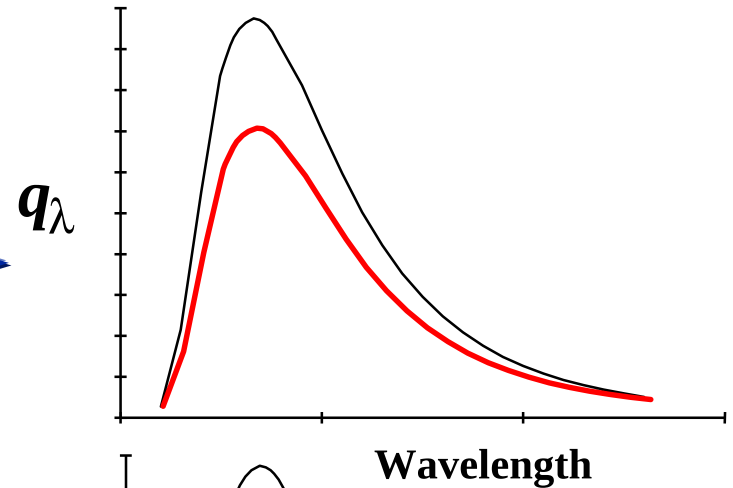
$$= \sigma T^4$$





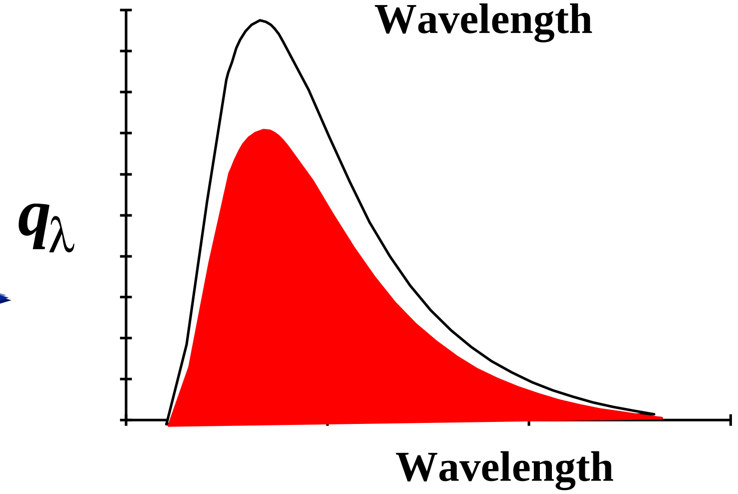
Emissivity

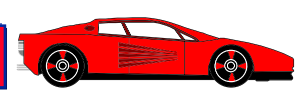
$$q_\lambda = \varepsilon \frac{2\pi hc^2\lambda^{-5}}{e^{ch/k\lambda T} - 1}$$



$$q = \int_0^\infty q_\lambda \, d\lambda$$

$$= \varepsilon\sigma T^4$$



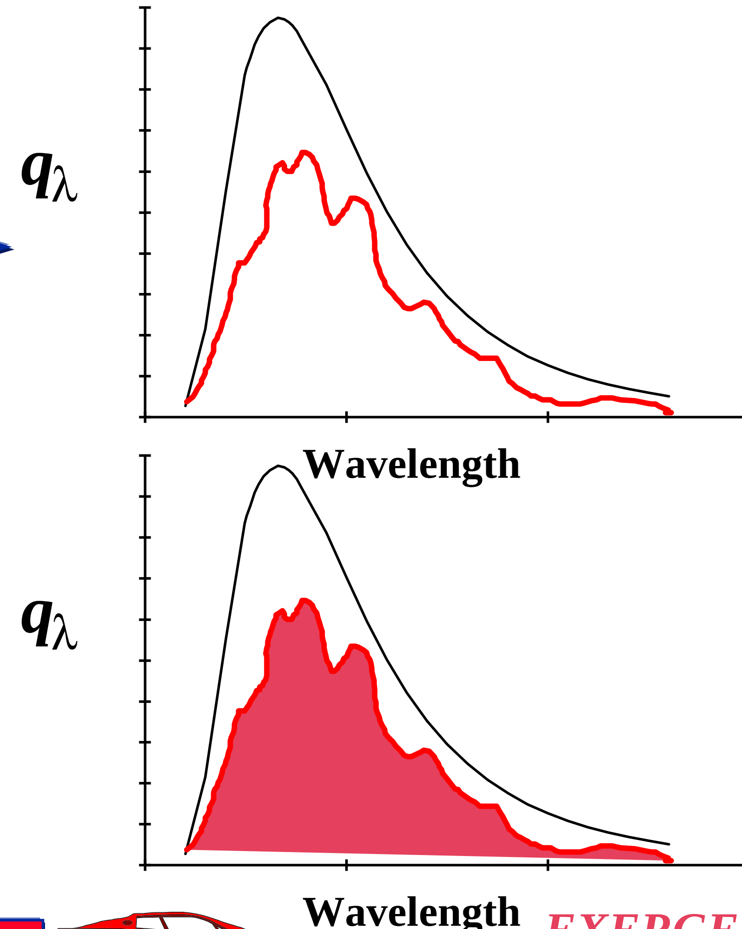


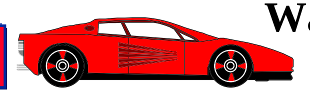
Wavelength Dependent Emissivity

$$q_\lambda = \varepsilon_\lambda \frac{2\pi hc^2\lambda^{-5}}{e^{ch/k\lambda T} - 1}$$

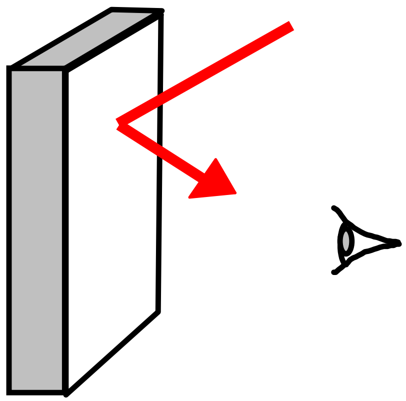
$$q = \int_0^\infty q_\lambda \, d\lambda$$

$$\neq \varepsilon\sigma T^4$$





Low Emissivity Surfaces

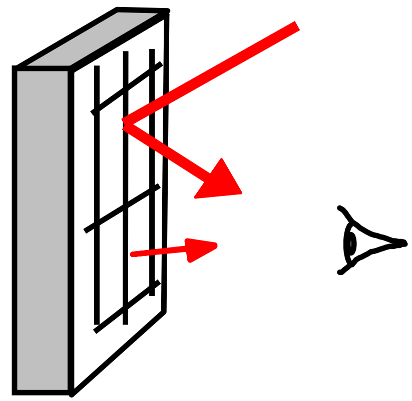


Perfect Mirror

Emissivity = 0.0
Reflectivity = 1.0

1.0

Theoretical

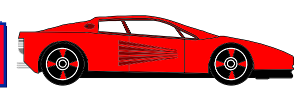


Poor Emitter

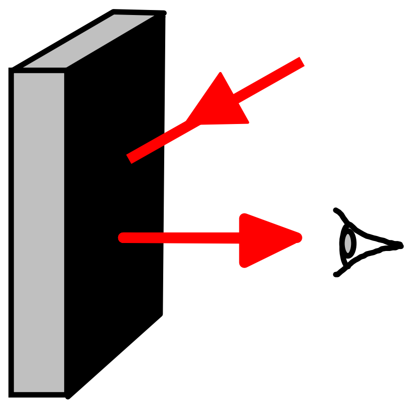
Emissivity = 0.1
Reflectivity = 0.9

1.0

Real: Uncoated Metals



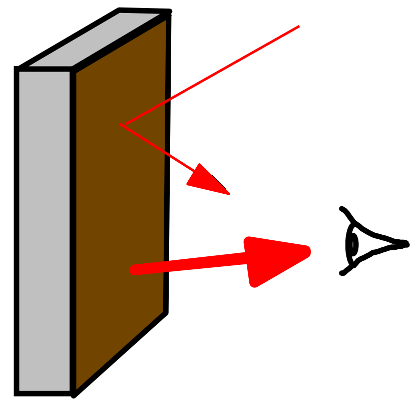
High Emissivity Surfaces



Perfect Blackbody

Emissivity = 1.0
Reflectivity = 0.0
―――
1.0

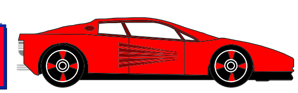
Theoretical



Good Emitter

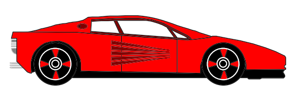
Emissivity = 0.9
Reflectivity = 0.1
―――
1.0

Real:
Non-Metals

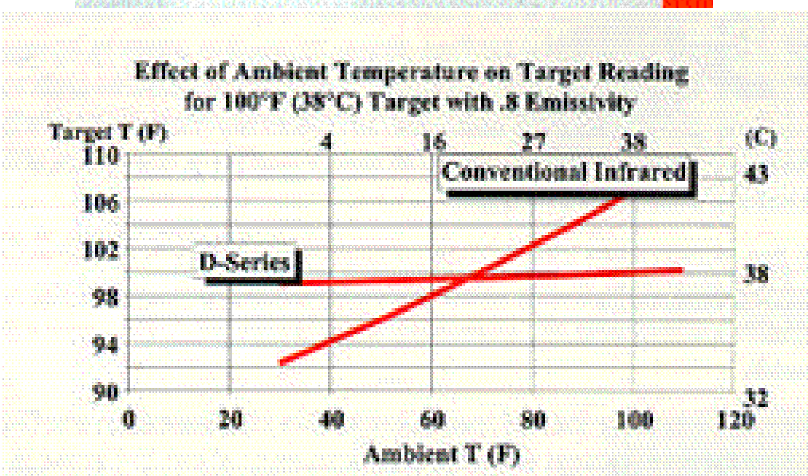


Measuring High Emissivity Surfaces

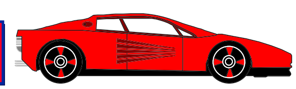
- **Use Sensors Designed For High Emissivity**
- **Calibrate Sensors to Actual Material in Production Process for High Accuracy**
- **Use D-Series to Determine Accurate Temperature for Calibration**



D-Series: Measure True Temperature for Calibration



- **Reflective cup provides true emissivity-free, and reflection-free temperature measurement**
- **Primary standard for calibration of IR sensor installations**

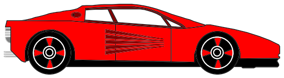


Measuring Low Emissivity Surfaces

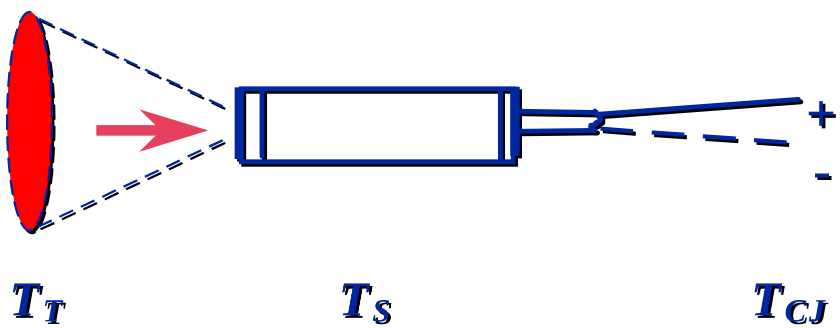
- **Coat the Surface, Then Use High Emissivity**

<u>If Not, Then</u>

- **Use Sensors Designed For Low Emissivity**
- **Calibrate Sensors to Actual Material in Production Process for High Accuracy**
- **Use D-Series to Determine Accurate Temperature for Calibration**
- **Use Cavities if Available on the Part**

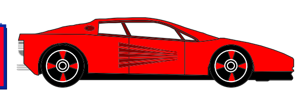


Principles of the IRt/c

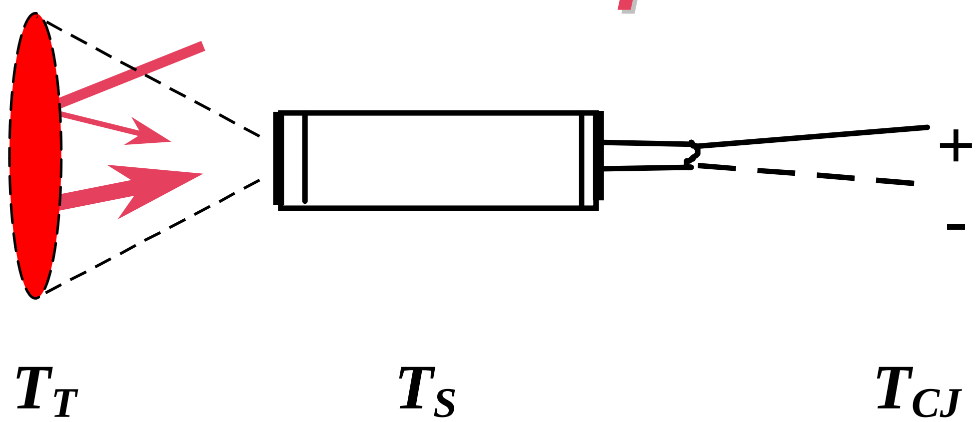


$$mV_{out} = c\ (T_T - T_S) + \alpha\ (T_S - T_{CJ})$$
$$= \alpha\ (T_T - T_{CJ}) \quad \text{when } c = \alpha$$
$$\alpha = \text{Seebeck coefficient}$$

- **No Power Required**
- **T/C Compatible**
- **0.0001°C Resolution**
- **0.01°C Repeatability**
- **Intrinsically Safe**
- **Simple, Rugged, Inexpensive**



Principles of the IRt/c

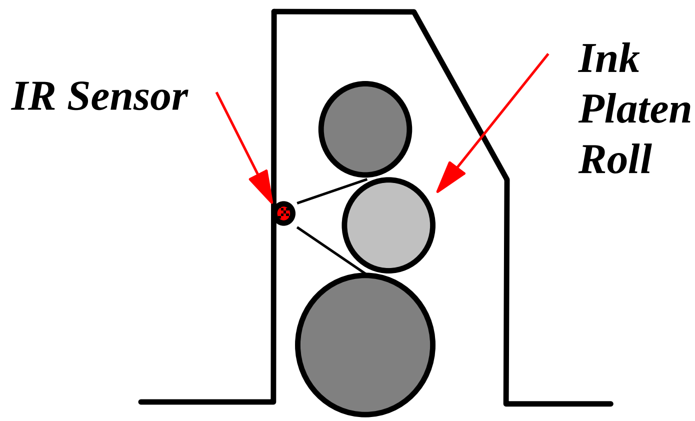


$$mV_{out} = c(\varepsilon T_T + (1-\varepsilon)T_S - T_S) + \alpha(T_S - T_{CJ})$$
$$= \alpha(T_T - T_{CJ}) \text{ when } (c\,\varepsilon) = \alpha$$
$$\alpha = \textit{Seebeck coefficient}$$

- **Calibrated to Real World Surfaces to Reduce Errors Caused by Emissivity < 1**
- **Optimum Temperature Range Selection for Highest Possible Accuracy in Real World Applications**

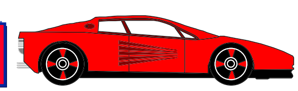
Compensates for the Ambient Reflections on Real Surfaces

Example of Improved Accuracy: Printing

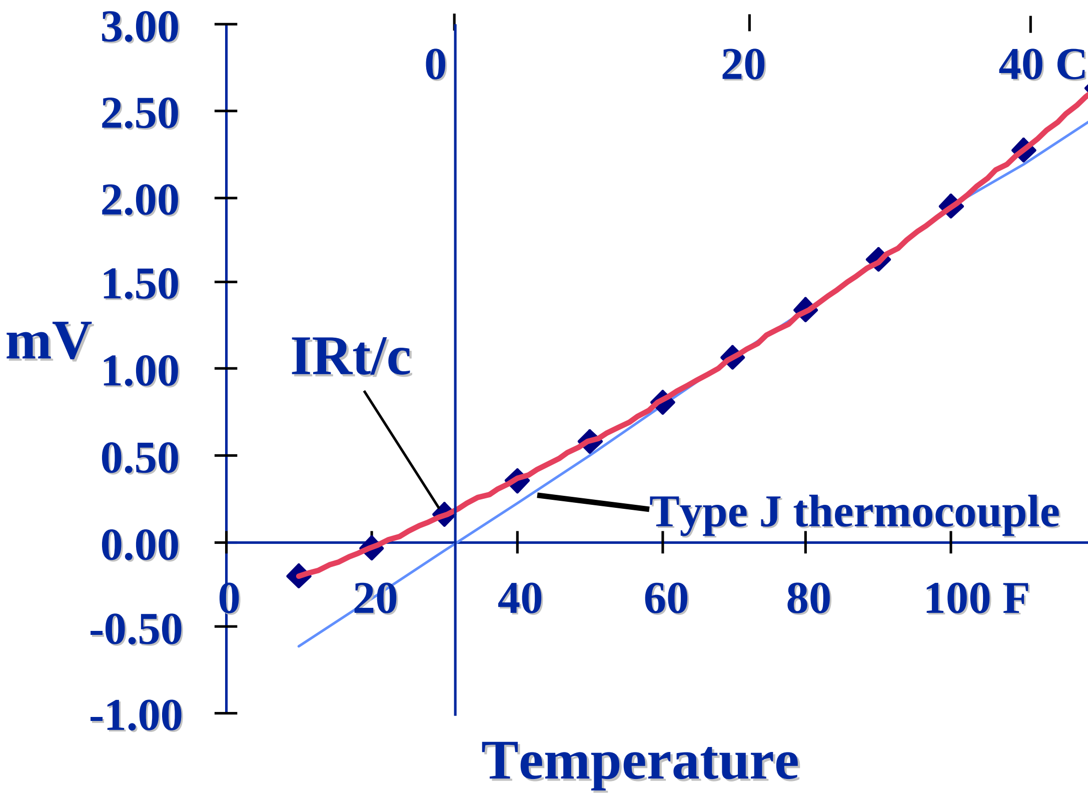


IR Temperature Control Accuracy:

Conventional IR	3°F (1.7°C)
IRt/c	0.2°F (0.1°C)



IRt/c Signal Output

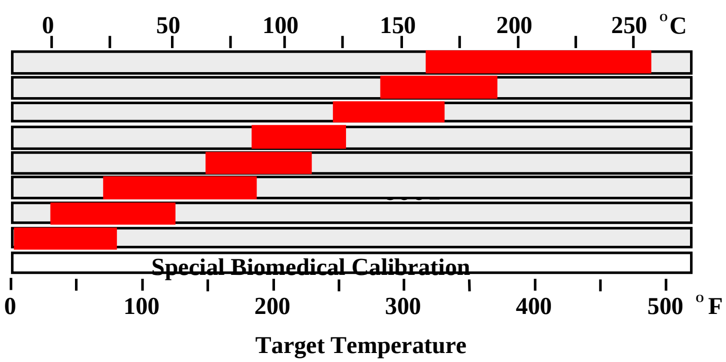


Increasing Production Speeds via IR -Controlled Heat Balance

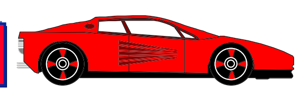
EXERGEN
CORPORATION

Optimum Temperature Range Selection for Highest Possible Accuracy in Real World Applications

Optimum Sensor Chart



Select Model Number	*Optimum Range*
IRt/c (*) - ** - 440F/220C	320 - 500F (160 - 260C)
IRt/c (*) - ** - 340F/170C	280 - 370F (140 - 190C)
IRt/c (*) - ** - 280F/140C	240 - 330F (115 - 165C)
IRt/c (*) - ** - 240F/120C	180 - 250F (80 - 120C)
IRt/c (*) - ** - 180F/90C	140 - 220F (60 - 105C)
IRt/c (*) - ** - 140F/60C	70 - 190F (20 - 90C)
IRt/c (*) - ** - 80F/27C	32 - 120F (0 - 50C)
IRt/c (*) - ** - 50F/10C	0 - 85F (-18 - 30C)
IRt/c (*) - ** - 98.6F/37C	Human Body Range



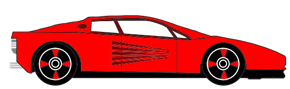
Signal Output Polynomials

For User Programming

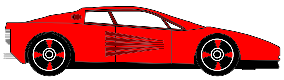
Master Polynomial Table for IRt/c Signal Output

(TT - CJT) = A*(mV)^6 + B*(mV)^5 + C*(mV)^4 + D*(mV)^3 + E*(mV)^2 + F*(mV) + G

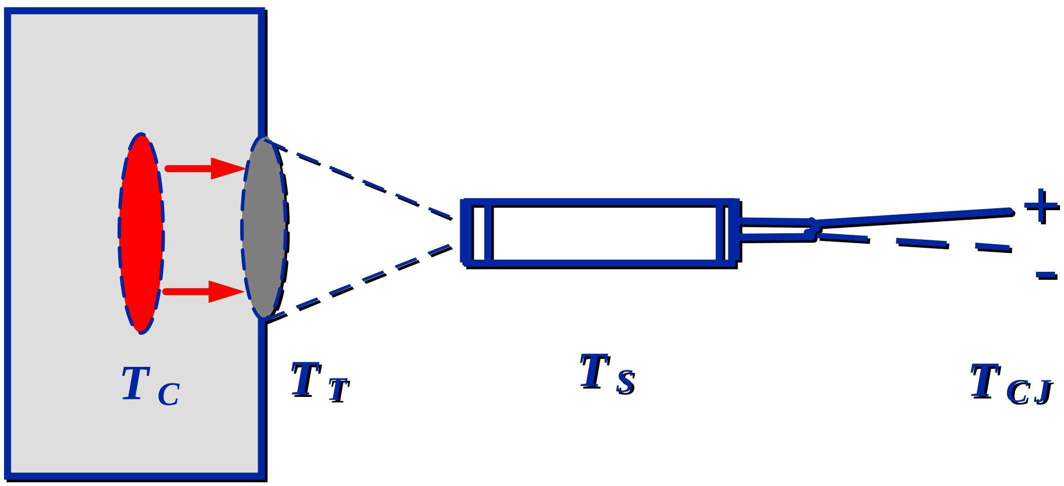
	A	B	C	D	E	F	G
IRt/c.xxx - J - 50F/10C	-6.14473E-09	2.08199E-06	-2.72953E-04	1.75317E-02	-5.84883E-01	1.53005E+01	0
IRt/c.xxx - J - 80F/27C	-2.83996E-08	7.41635E-06	-7.54046E-04	3.79224E-02	-1.00406E+00	2.06592E+01	0
IRt/c.xxx - J - 140F/60C	-4.31591E-08	1.06077E-05	-1.01002E-03	4.72155E-02	-1.14872E+00	2.20397E+01	0
IRt/c.xxx - J - 180F/90C	-7.03138E-08	1.59317E-05	-1.39844E-03	6.02655E-02	-1.35167E+00	2.39075E+01	0
IRt/c.xxx - J - 240F/120C	-1.05707E-07	2.23776E-05	-1.83521E-03	7.38926E-02	-1.54843E+00	2.55885E+01	0
IRt/c.xxx - J - 280F/140C	-1.89514E-07	3.63996E-05	-2.70839E-03	9.89395E-02	-1.88106E+00	2.82034E+01	0
IRt/c.xxx - J - 340F/170C	-2.99852E-07	5.33519E-05	-3.67751E-03	1.24452E-01	-2.19192E+00	3.04447E+01	0
IRt/c.xxx - J - 440F/220C	-5.20472E-07	8.44263E-05	-5.30444E-03	1.63572E-01	-2.62438E+00	3.31770E+01	0



Thermal Energy Balance in Space and Time: The Space Domain



Principles of the IRt/c: With Heat Balance

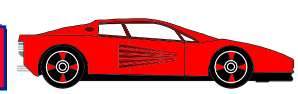


- **Automatically Computes Heat Balance, Using Material Properties Alone**
- **Can be Configured for Unpowered or Powered Configurations**

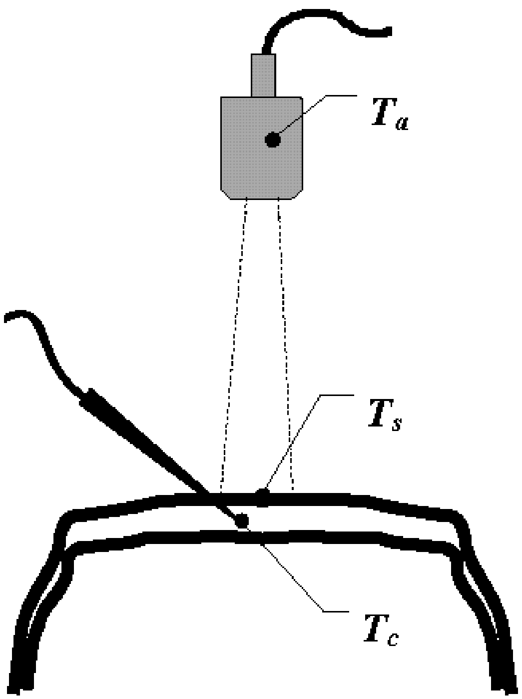
$$mV_{out} = c((T_C - T_S)(1/k) + T_S - T_S) + \alpha(T_S - T_{CJ})$$

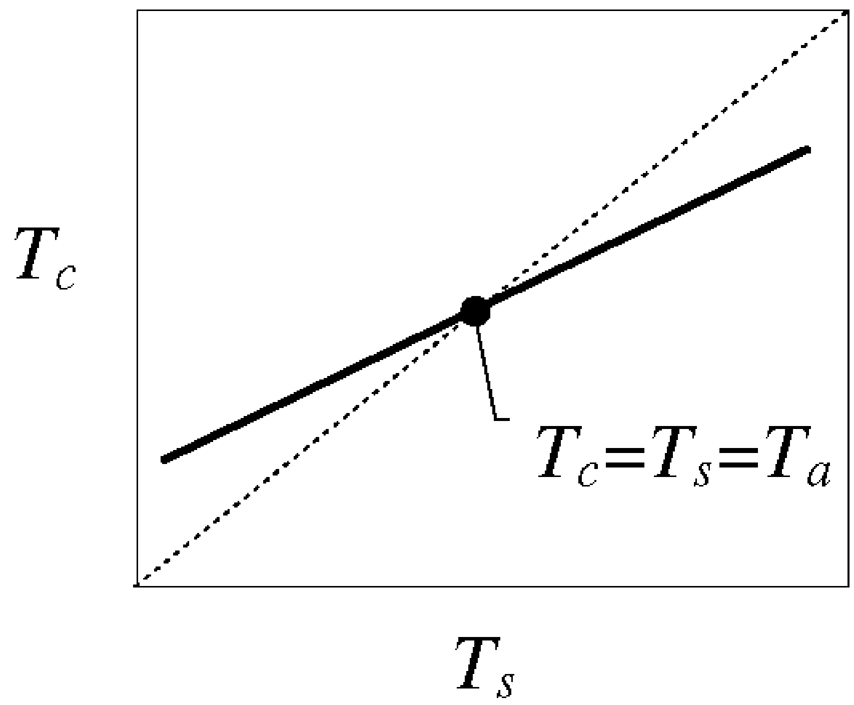
$$= \alpha(T_C - T_{CJ}) \quad \text{when } c = (\alpha k)$$

$$\alpha = \text{Seebeck coefficient}$$

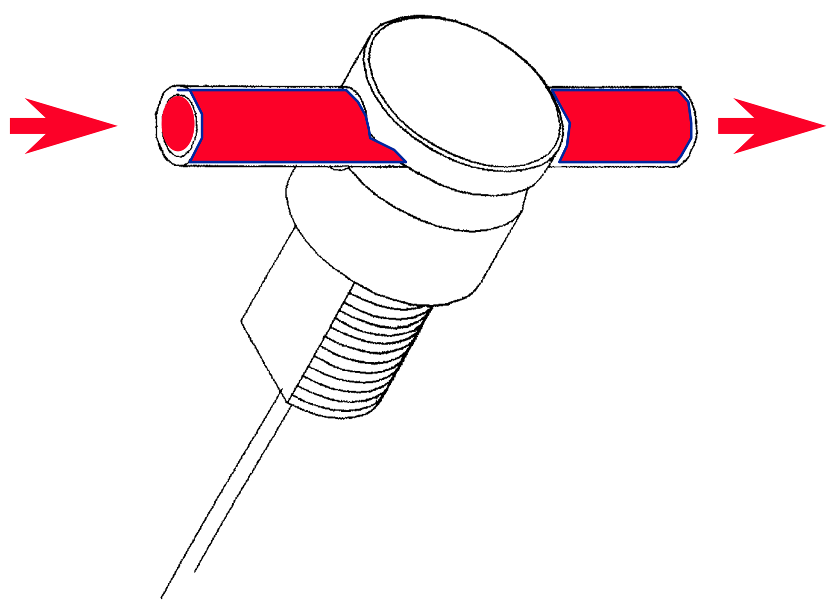


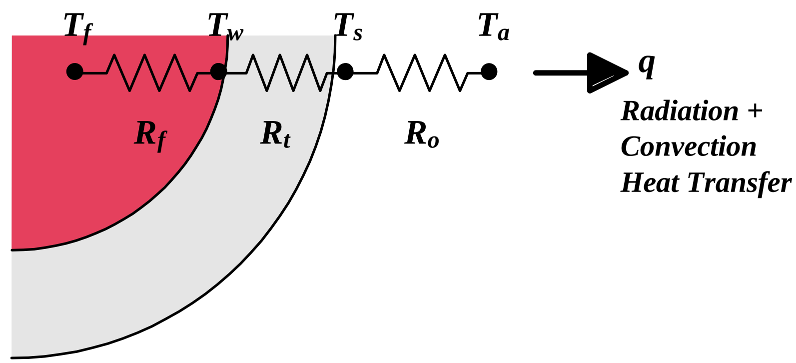
Heat Balance Example: Internal Tire Temperatures



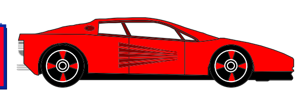


Non-Invasive Fluid Temperature in Tubing via IRt/c Heat Balance

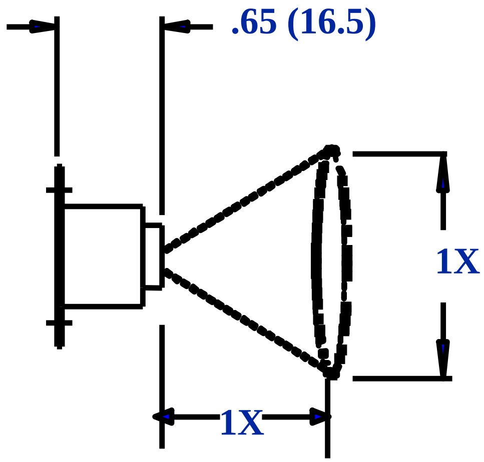


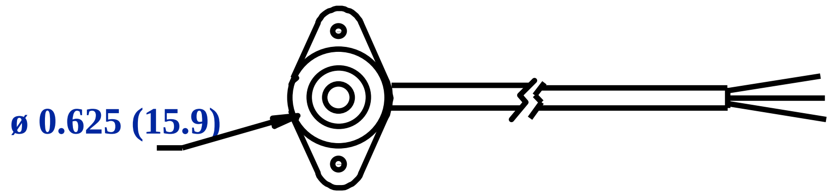


$$T_f = \frac{R_f + R_t + R_o}{R_o}(T_s - T_a) + T_a$$



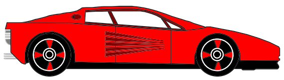
Ultra-Miniature Infrared Thermocouple With Heat Balance





Thermal Energy Balance in Space and Time:

The Time Domain



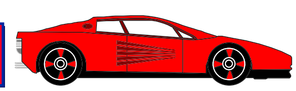
Jean Baptiste Joseph Fourier
1768-1830

- **Fourier's Equation of Heat Conduction**

$$\left(\frac{q}{A}\right)_x = -k\frac{\partial T}{\partial x}$$

- **Unsteady State Heat Conduction for Moving Materials**

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\kappa}\frac{\partial T}{\partial t}$$



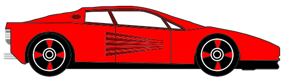
Pierre Simon Marquis de LaPlace
1749 -1827

- **Laplace Transform Method of Solution**

$$\bar{T}(x,s) = \int_0^\infty e^{-st} T(x,t)\,dt$$

- **Converts Partial Differential Equation to Ordinary Differential Equation**

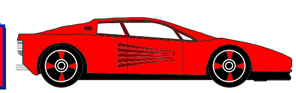
$$\frac{d^2\bar{T}}{dx^2} - \frac{s}{\kappa}\bar{T} = \frac{T_o}{\kappa}$$



Francesco Pompei
1948 -

- **New Method of Solution Leads to a General Equation for Non-Contact Temperature Monitoring of <u>Internal</u> Temperatures of Moving Materials**

$$T_c = \frac{h\sqrt{\tau\kappa}}{k}\sinh\left(\frac{a}{\sqrt{\tau\kappa}}\right)\left(T_s - T_\infty\right) + T_s + \left[\cosh\left(\frac{a}{\sqrt{\tau\kappa}}\right) - 1\right]\left(T_s - T_0\right)$$



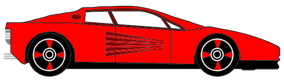
- **Which simplifies to**

$$T_c = K_1(T_s - T_\infty) + T_s + K_2(T_s - T_o)$$

where

$$K_1 = \frac{1}{a}\sqrt{\tau\kappa}\,\frac{ha}{k}\sinh\left(a\sqrt{\frac{1}{\tau\kappa}}\right) \quad , \quad K_2 = \left(\cosh\left(a\sqrt{\frac{1}{\tau\kappa}}\right) - 1\right)$$

$$\frac{1}{a}\sqrt{\tau\kappa} = (Fo)^{1/2} \quad , \quad and \quad \frac{ha}{k} = Bi$$



Deriving The Speed Boost Equation

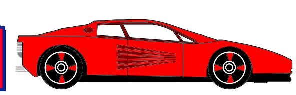
$$T_c = K_1(T_s - T_\infty) + T_s + K_2(T_s - T_o)$$

- Set the surface temperature equal to the center temperature, then the equation reduces to

$$T_c = T_s$$

$$\frac{(T_\infty - T_s)}{(T_s - T_o)} = \frac{K_2}{K_1}$$

- Since K_2/K_1 is a function only of material properties and speed:

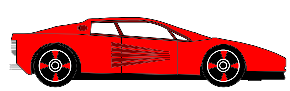


The ratio can be formed, which then becomes:

The Speed Boost Equation

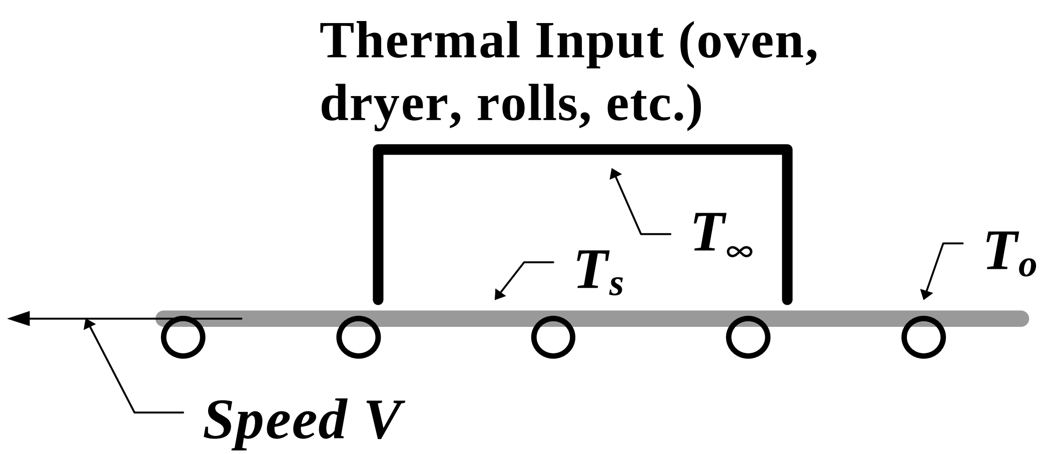
$$\frac{V_{new}}{V_{old}} = \frac{\left(\overline{\Delta T}\right)_{new}}{\left(\overline{\Delta T}\right)_{old}}, \quad where\ \overline{\Delta T} = \frac{T_{\infty} - T_s}{T_s - T_o}$$

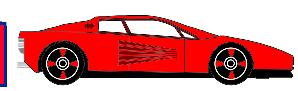
- **General Equation for Non-Contact IR Temperature Monitoring of <u>Internal</u> Temperatures of Moving Materials is Combined with Surface Temperature**
- **Leads to Uniform Material Temperature When Controlled via the *<u>Speed Boost Equation</u>***
- **Which Forces the Control System to Apply Heat at an Optimally *<u>Balanced</u>* Rate**



Applying
The Speed Boost Equation

$$\frac{V_{new}}{V_{old}} = \frac{\left(\overline{\Delta T}\right)_{new}}{\left(\overline{\Delta T}\right)_{old}}, \quad where\ \overline{\Delta T} = \frac{T_\infty - T_s}{T_s - T_o}$$

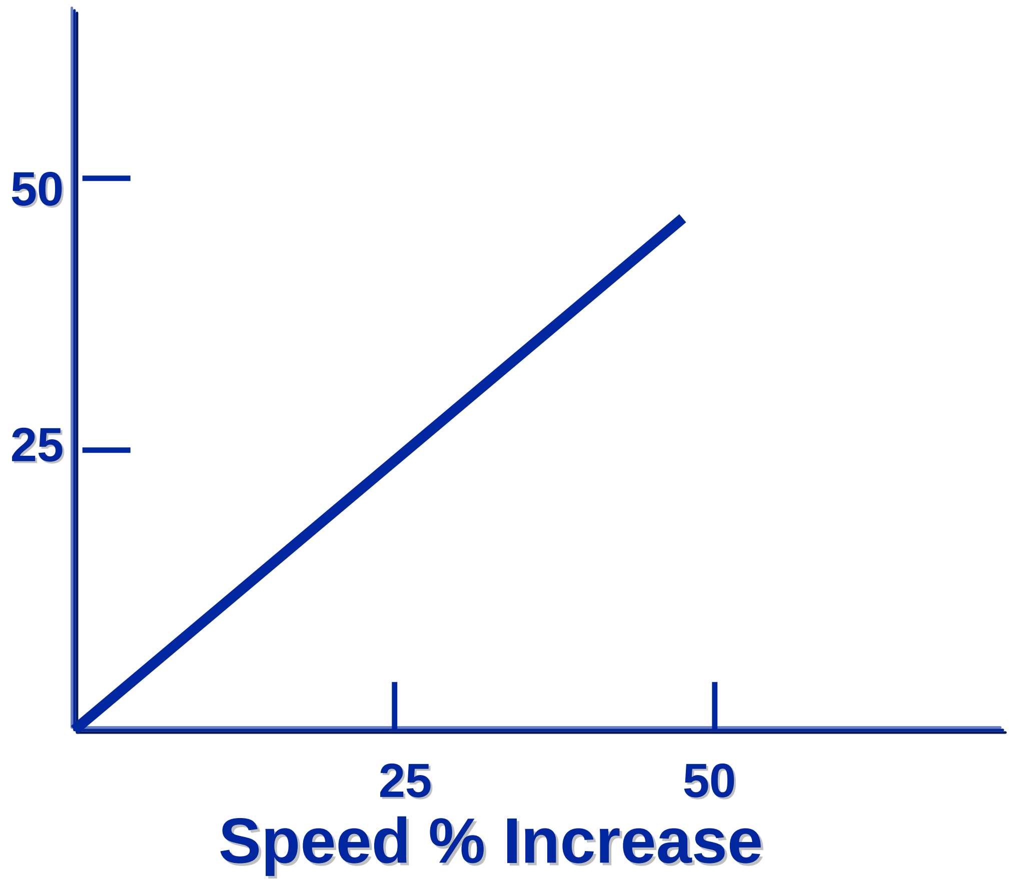


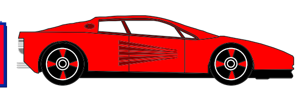


Speed Boost Equation is Generally Linear for Most Applications

$$\overline{\Delta T} = \frac{T_\infty - T_s}{T_s - T_o}$$

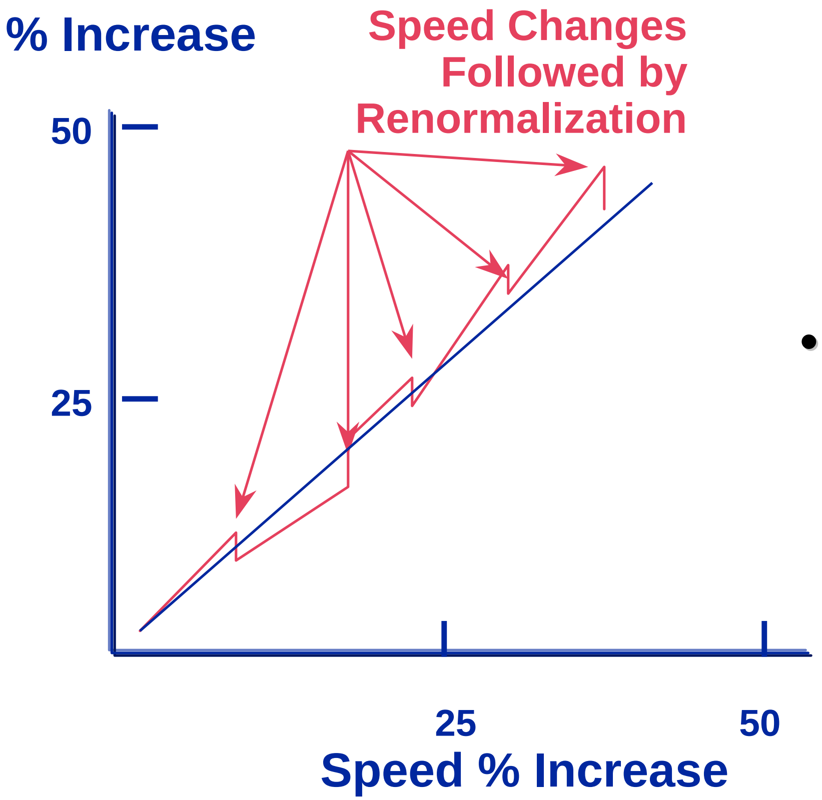
% Increase



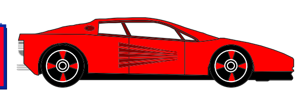


Implementing Speed Boost to Include Non-Linearities

$$\overline{\Delta T} = \frac{T_\infty - T_s}{T_s - T_o}$$

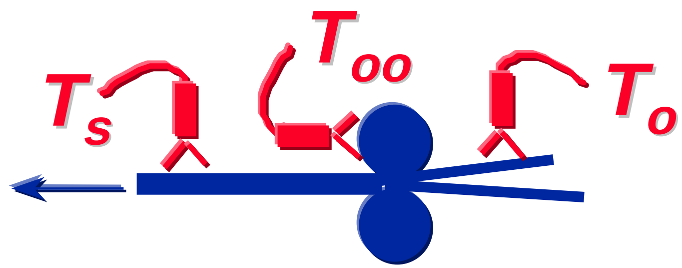


- **Apply step-wise speed increases in accordance with speed boost equation, and renormalize at new operating condition to account for property changes.**
- **For variable speed systems, program to follow the characteristic curve.**



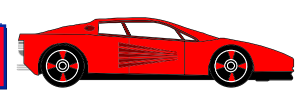
Example Speed Boost: Laminating

- **Existing Set-up:**
  - T_{oo} = 105 C
  - T_s = 85 C
  - T_o = 25C
- **New Set-up:**
  - T_{oo} = 120 C
  - T_s = 85 C
  - T_o = 25C
- **Potential Speed Increase*:**
  - $\Rightarrow$ 25%



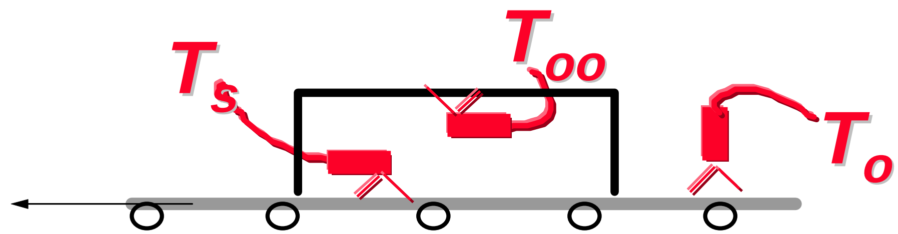
$$\overline{\Delta T} = \frac{T_\infty - T_s}{T_s - T_o}$$

*Assuming all other factors are permitting



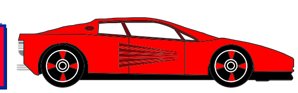
Example Speed Boost: Drying

- **Existing Set-up:**
  - T_{oo} = 260 C
  - T_s = 85 C
  - T_o = 25 C
- **New Set-up:**
  - T_{oo} = 260 C
  - T_s = 85 C
  - T_o = 40 C (with preheat)
- **Potential Speed Increase*:**
  - ⇒ 33%

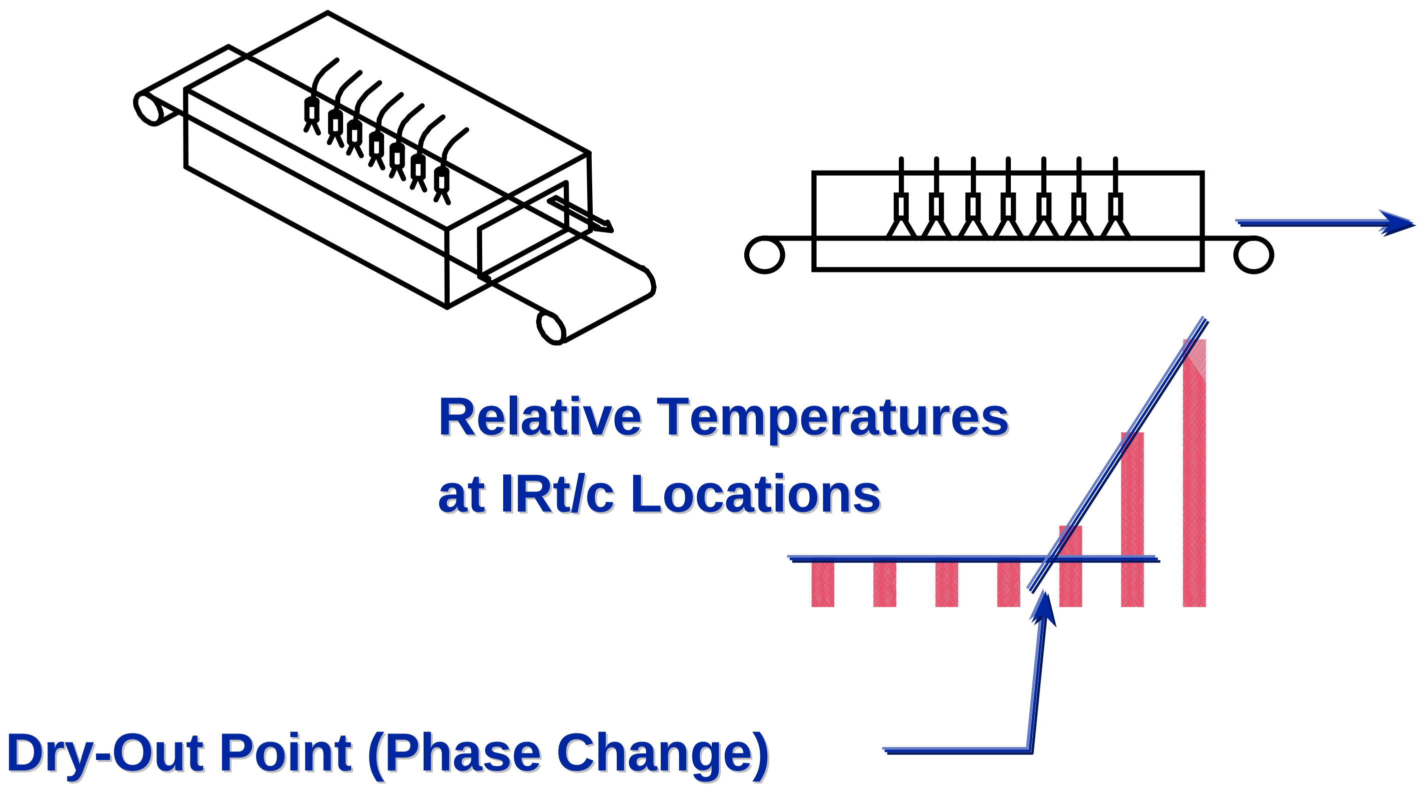


$$\overline{\Delta T} = \frac{T_\infty - T_s}{T_s - T_o}$$

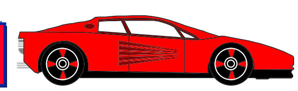
*Assuming all other factors are permitting



Precision Drying Control for Maximum Production Speed



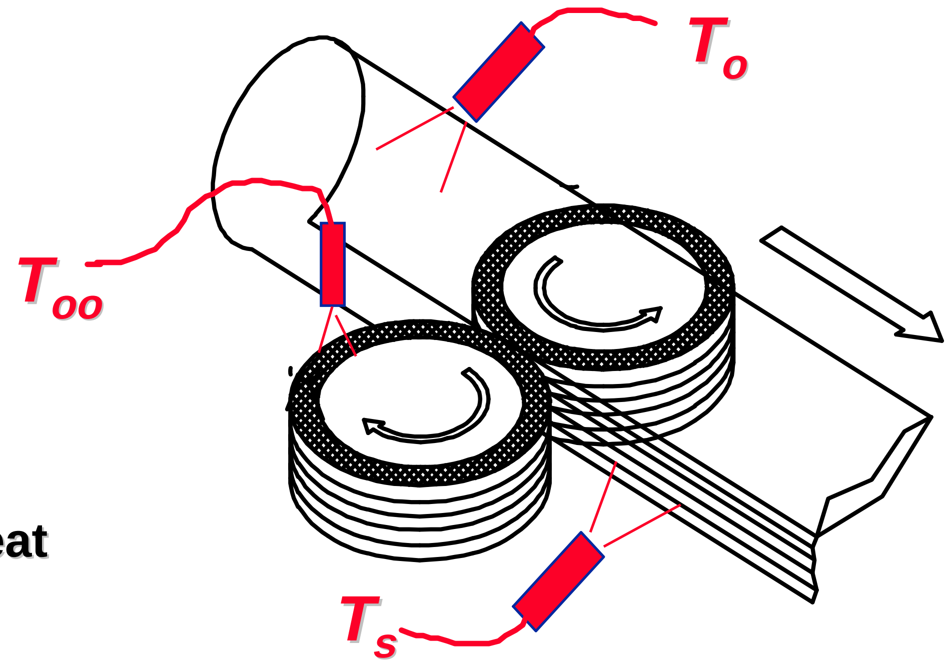
Increasing Production Speeds via IR -Controlled Heat Balance



EXERGEN
CORPORATION

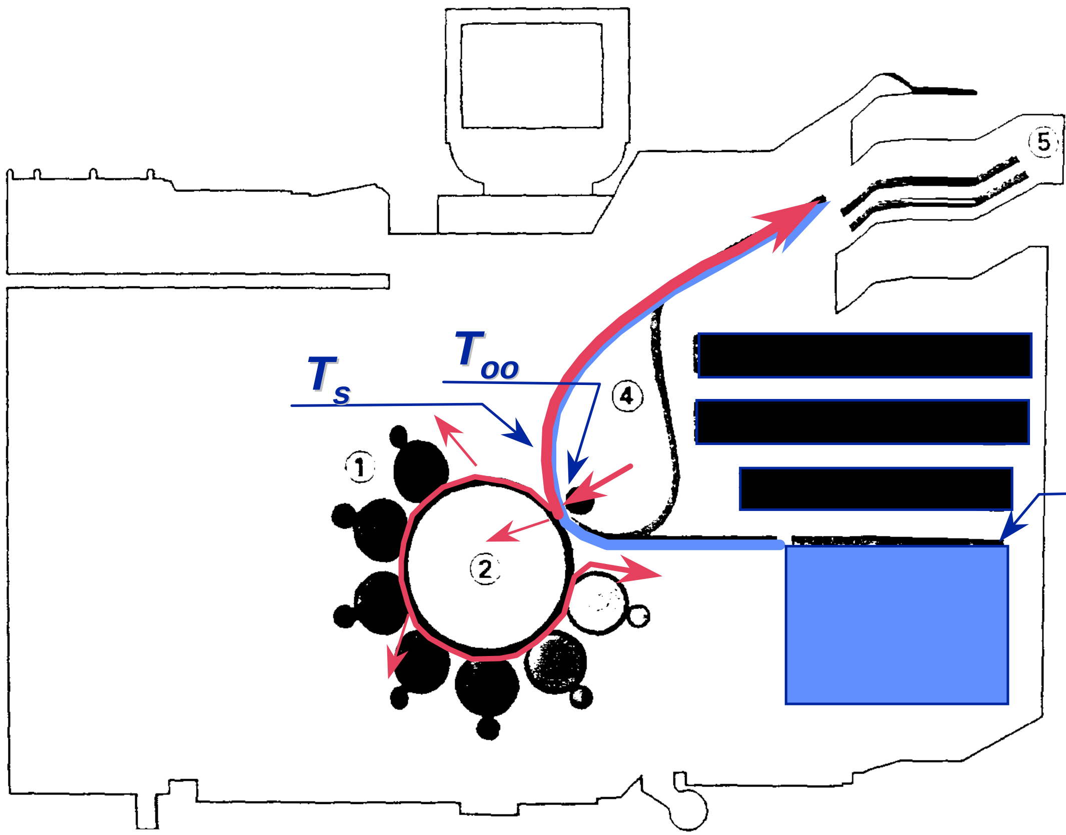
Example Speed Boost: Heat Sealing

- **Existing Set-up:**
  - T_{oo} = 150 C
  - T_s = 120 C
  - T_o = 25 C
- **New Set-up:**
  - T_{oo} = 150 C
  - T_s = 120 C
  - T_o = 45 C (with preheat added)
- **Potential Speed Increase:**
  - $\Rightarrow$ 27%



$$\overline{\Delta T} = \frac{T_\infty - T_s}{T_s - T_o}$$

Example: High Speed Color Copy Process

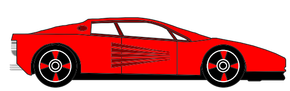


Paper Flow

Energy Flow

$$\overline{\Delta T} = \frac{T_\infty - T_s}{T_s - T_o}$$

Increasing Production Speeds via IR -Controlled Heat Balance



EXERGEN
CORPORATION

Speed Boost Equation

$$\frac{V_{new}}{V_{old}} = \frac{\left(\overline{\Delta T}\right)_{new}}{\left(\overline{\Delta T}\right)_{old}}, \quad where\ \overline{\Delta T} = \frac{T_{\infty} - T_s}{T_s - T_o}$$

- **Above Can Be a Simplified Control Algorithm**

$$T_{\infty} = \left(\overline{\Delta T} + 1\right)\left(T_s\right) - \left(\overline{\Delta T}\right)\left(T_o\right)$$

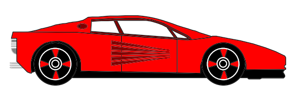
Product Surface - setpoint (T_s)

Heat Source Temperature (T_{∞})

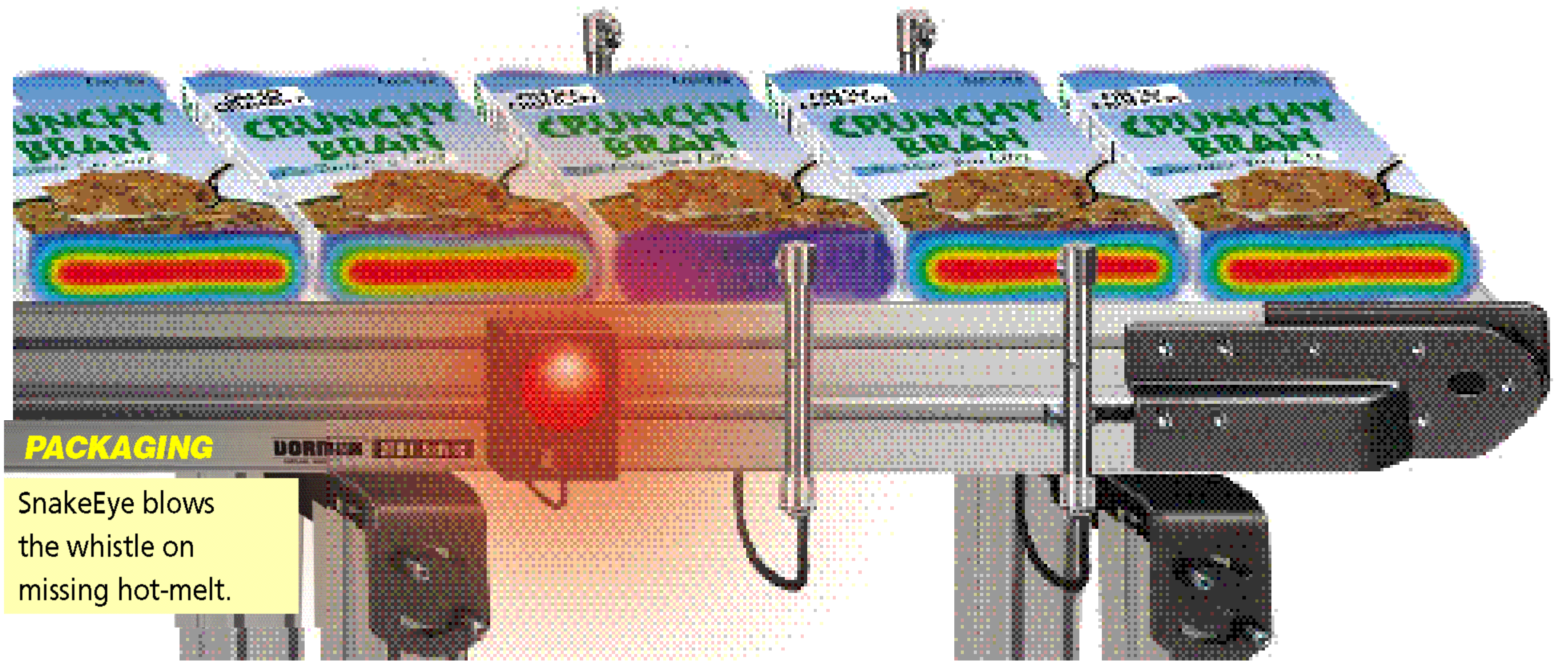
Control Loop Gain ($\overline{\Delta T}$)

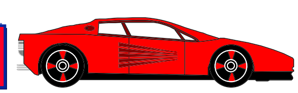
Product Input (T_o)

- **Keep Equation Balanced to Within a Few % to Avoid Non-Uniformity in Material Temperature**



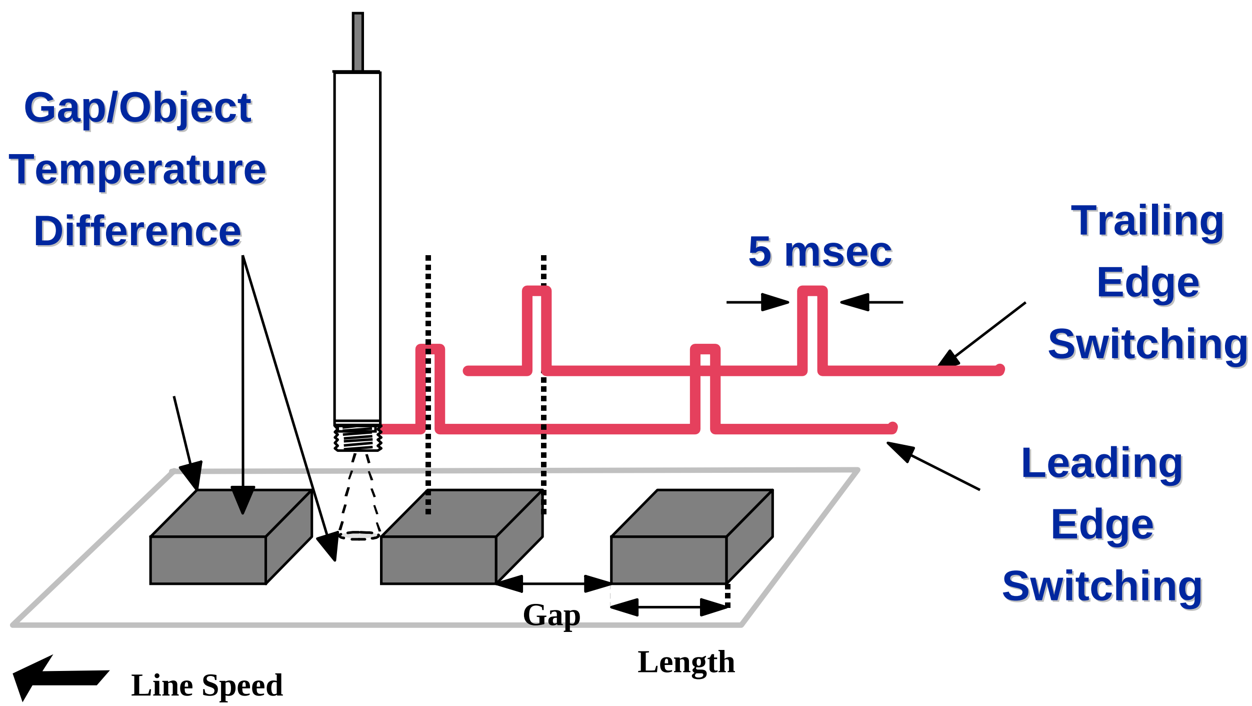
SnakeEye Photocell-Like Non-Contact Thermal Inspection





SnakeEye Photocell-Like Non-Contact Thermal Switches

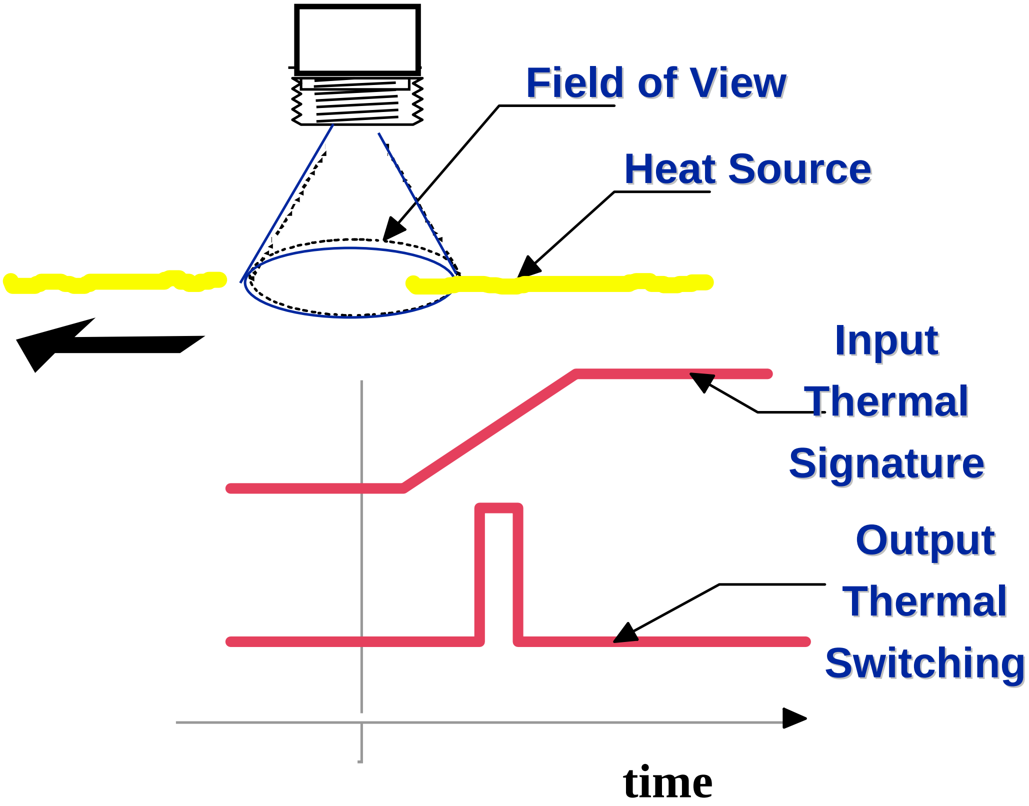
Thermal Switching of Objects With Less Than 1°C Differential



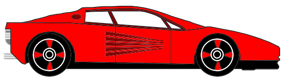
Increasing Production Speeds via IR -Controlled Heat Balance

EXERGEN CORPORATION

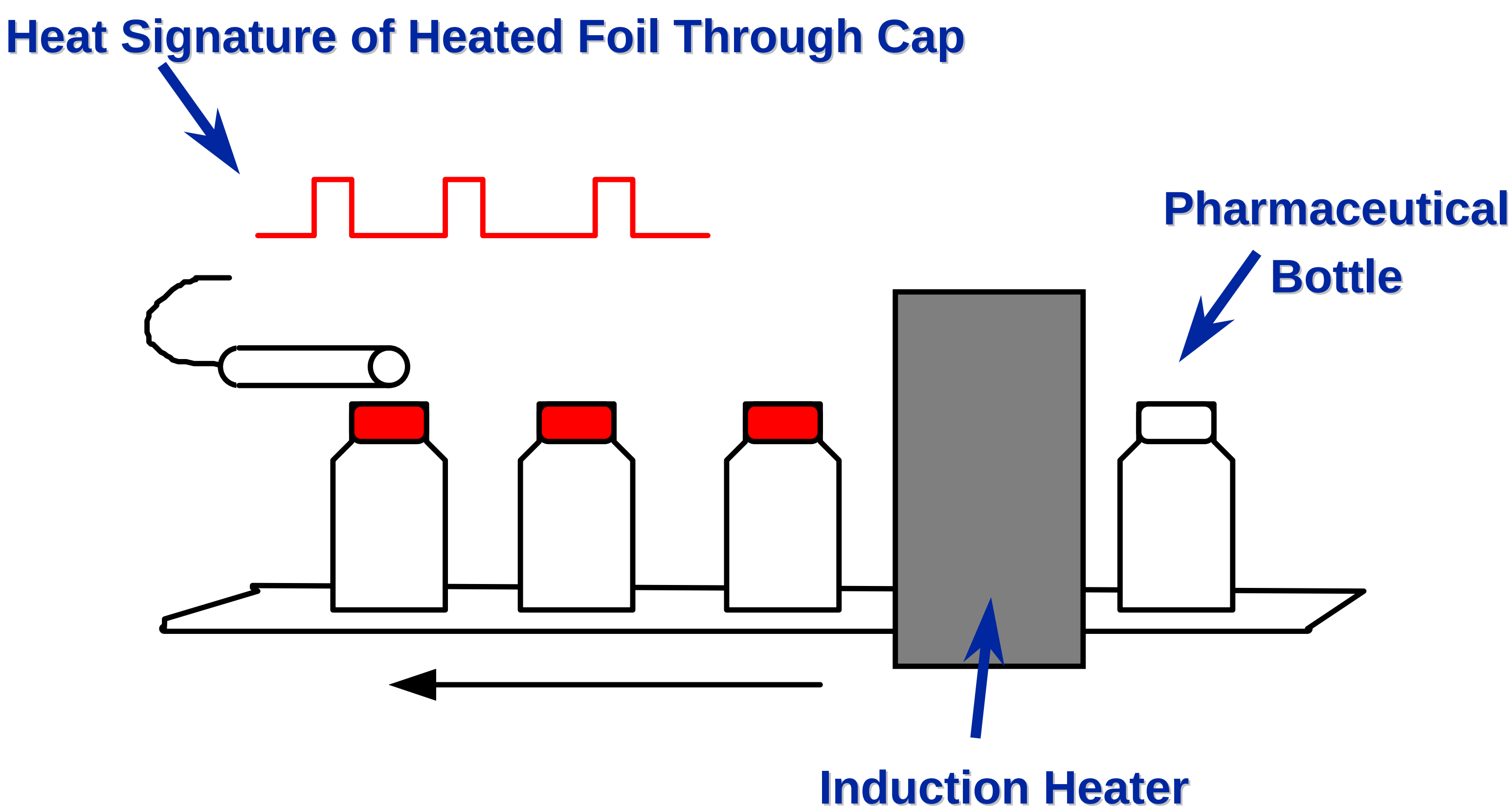
Principles of the SnakeEye



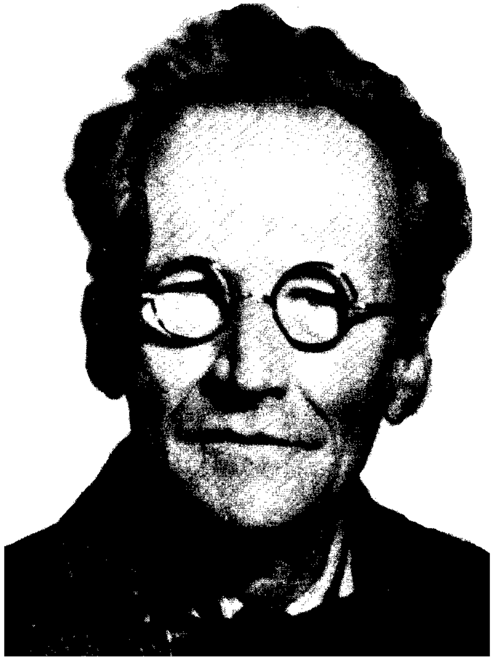
- The heat source enters the field-of-view of the SnakeEye and is detected by the sensing system.
- If the rate of change is of sufficient magnitude the SnakeEye causes the output to switch.



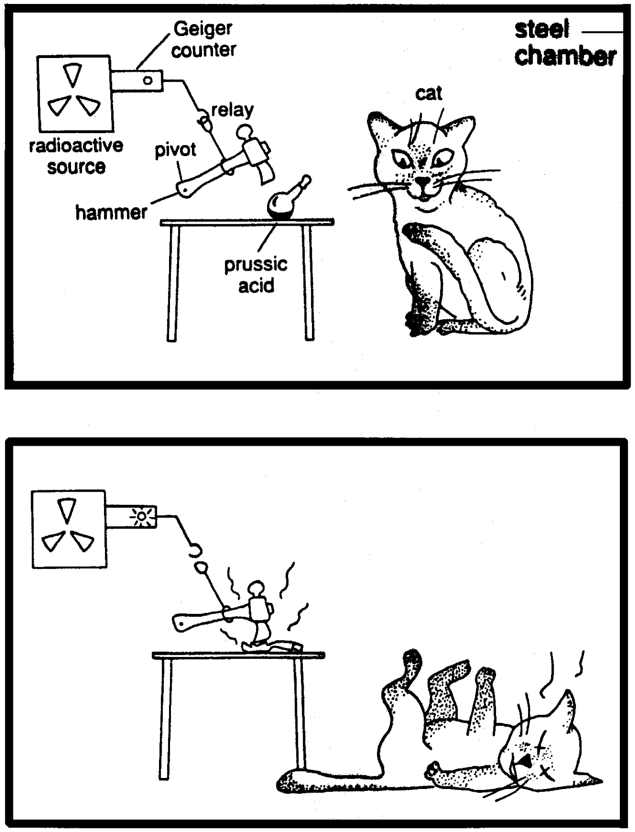
Detecting Presence/Absence Hidden Foil Safety Seal



Erwin Schrodinger ~ 1935



- **The Cat Paradox**

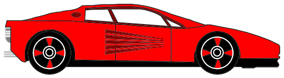


You Cannot Know For Sure That the Product is Right Unless You Look...

With

EXERGENIR

Sensors



The Exergen Creed

We are the best in the world at what we do,

And our products and services must be commensurate with our mission of supplying our customers with the best,

To help them be the best in the world at what <u>they</u> do.

F. Pompei
President and Founder